An Expert System for Concrete Diagnosis

by

Gehad Mohammed Hamed

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

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COLLEGE OF GRADUATE STUDIES

بسم الله الرحمن الرحيم

وَقُلْ رَبِّ زِدْنِي عِلْمًا

To my beloved Parents . .

To the inspiration of my late brother . .

To the supporting elder brother. .

To the loving sister . .

Your efforts cannot be duly appreciated;

Your tender care cannot be ignored.

To you all, this work is dedicated

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ABSTRACT

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Concrete is a material liable to deterioration attributable to either external or internal influences. Diagnosing a defect can be established through identification and determination of its dominant cause. In this study, a knowledge-based system, "*CONCEXS*", is developed to diagnose several concrete defects frequently occurring in concrete slabs, beams, and columns. This study addresses the salient notions of concrete diagnosis and particularly handles some deterioration problems for which relevant testing techniques are summarized. The knowledge base is acquired from literature expertise and domain experts then employed to analyze existing defect cases in Saudi Arabia. Defects' attributes are heuristically formulated into decision trees that are suitable for encoding as production rules. *CONCEXS*-user interface is efficiently interactive by means of call up menus thus guiding the user through the diagnostic process. The system utilizes simple linguistic values which exhibit friendly interaction during a consultation session. Verification and validation of *CONCEXS* were executed, and proved its capability of deducing diagnostic decisions satisfactorily.

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تتعرض الخرسانة لعدة عوامل داخلية أو خارجية قد تؤثرعلي أداء الخرسانة وفقدانها لكثير من خواصها والتي أهلتها لتؤدي وظيفتها البنائية. ولكي نتمكن من تشخيص هذه العيوب يجب أولا ان يتم تحديد هذا العيب ثم استنتاج السبب أو العامل الذي أدي لحدوثه. وقد وفر الكمبيوتر بتعدد مجالاته امكانية تطوير مايسمي بانظمة الخبرة في العديد من مجالات التشخيص, ومن ضمنها مجال تشخيص عيوب الخرسانة بتنوع استخداماتها. تناقش هذه الاطروحة امكانية تصميم نظام خبرة ليقوم بمهمة تشخيص عيوب الخرسانة في المباني السكنية مع التركيز علي عيوب البلاطات والكمرات والاعمدة الخرسانية. ويعتمد نظام الخبرة علي قاعدة معلومات عن الخرسانة تم تجميعها واستنباطها من الخبراء بهذا المجال ثم تطبيقها علي حالات تدهور لمباني حدثت بالمملكة العربية السعودية. ولقد استخدم أسلوب لعرض المعلومات الدالة علي خواص الخرسانة في شكل بياني تسلسلي لاتخاذ القرار. وبعد عرض وتنسيق العلاقات يتم كتابتها في هيئة استنباطات. ويتميز النظام المصمم بعدة خواص جذابه مثل النوافذ التي تظهر وتقوم بوظيفة ارشاد المستخدم وتوجيهه اثناء الاستشارة. ويستخدم النظام قيم لغوية ميسرة لتساعد المستخدم علي فهم طبيعة المشكلة وايضاح متطلبات التشخيص. ولقد تم تجربة النظام علي حالات تصدع في المنطقة واثبت فعالية وكفاءة في تشخيص الحالة وتحديد سببها.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران - المملكة العربية السعودية

CHAPTER 1

INTRODUCTION

1.1 Background

A concrete structure would be considered durable if it fulfilled its intended duty for the whole of its design life with the minimum level of maintenance. It would be unrealistic to expect any structure to maintain its "as new" condition without any maintenance whatever.

Concrete has the potential of an almost unlimited life unless it is subjected to chemical attack by an aggressive environment, or suffers physical damage. Weather staining and similar discoloration should not be confused with lack of durability. On the other hand, deep carbonation, chemical attack, cracking and spalling due to poor quality materials or workmanship, and/or corrosion of reinforcement, would be a clear case of low durability. It is essential to understand how these various causes are likely to reveal themselves, so that a realistic assessment of the overall causes can be made and a proper diagnosis may be achieved. The essential factor in such investigation is the ability to recognize at an early stage the likely causes of defects and to direct the inspection accordingly.

The effort input in this study revealed that there is a real need for a regular and thorough system of inspection of reinforced concrete structures. As a result, any deterioration can be detected and recorded at its early stage, and a decision taken on what remedial work if any should be carried out. Any effort to establish such a programmed systematic approach for diagnosis will be highly appreciated. The only hindrance to facilitate such a system is the tremendous amount of information that should be dealt with in order to furnish a solid database required to come up with a suitable maintenance or repair decision.

Moreover, there are numerous methods and combinations of methods to repair deteriorated concrete. The selection of the proper technique is dictated by case-specific conditions. Unfortunately, the ranges of applicability of the methods are not clearly defined with respect to the relevant parameters, nor are most values of the parameters that characterize a given situation. This is quite a usual case in the field of maintenance of concrete structures, in which experience often plays a vital role.

The nature of concrete investigation and diagnosis problem and paucity of experts, make this domain attractive for the development of a knowledge-based system.

The Kingdom of Saudi Arabia has built a large stock of housing and public service buildings over the last decade. Maintaining those buildings is very important for the welfare of this country. Saudi Arabia has also a shortage in building maintenance experts. Providing an expert system for building maintenance for low level maintenance technicians will reduce the need for a large number of skilled staff, usually imported from outside the country.

1.2 Problem Statement and Significance

"Define systematically the causes of structural building defects, and identify and recommend a procedure for repairing them by using knowledge-based systems approach."

Building maintenance covers a wide range of areas; building structure, exterior finishes, roofing, interior finishes, site improvements and mechanical, electrical and HVAC systems. This study will try to develop knowledge relevant to the maintenance of the structural systems in a building, not the mechanical/electrical/plumbing. Within each area, the possible range of material and member types, condition evaluation, and diagnosis procedures will be defined as a basis for the development of the expert system. In particular, concrete structural elements such as slabs, columns, beams, constitute the building maintenance domain for the knowledge base system. The nature of expert systems will allow the investigators to add other maintenance domains in the future. The benefits of this study will accrue to contractors and building owners, both of small residential buildings and of large commercial and institutional structures.

It might be raised that why should we investigate defects? A crack is a crack, and investigations take time and cost money. Why do not we just fix it and move on to the next existing problem?. Such questions are irrational; it is obvious that the disease and not the symptoms should be treated. The difficulty is that, when dealing with concrete structures, the disease is often well hidden behind the symptoms and the symptoms are common to many diseases. The aim of this research is therefore to help engineers to identify the causes of defects so that relevant and long-lasting -not cosmetic- remedial action can later be investigated in future research work. This will be done by identifying and categorizing the defects and establishing the methods of investigation which can be applied to diagnose their cause.

What makes diagnosis difficult is the large amount of knowledge and experience it requires. This knowledge may cover, but not be limited to: (Rauch, Hindin, 1988)

1. It requires knowledge of the system and how it functions normally.
2. It requires gathering information about the failed element and its defect symptoms.

3. It requires knowledge of the relevant information to the defect that should be collected.
4. It requires the ability to use the knowledge about the system and the information gathered to explain how the defect could have occurred.
5. It requires the ability to form a hypothesis and perform some tests to get back more information that either confirms or denies the hypothesis.

The process of gathering information and formulating and testing hypotheses may need to be done several times in order to test their validity Fig 1.1. A successful diagnosis can only be achieved at the end of this process. Unfortunately, few people appear to have this body of knowledge necessary to make them good troubleshooters. Those that do, tend to be promoted so that they do not use their troubleshooting expertise anymore. The remaining troubleshooters may be competent, but they lack the spark and instincts that made the expert unique.

Knowledge systems offer a way to preserve and protect a troubleshooter's expertise and to make that expert troubleshooter a consultant to many people. The idea is to encode as much as possible of the expert's wisdom, judgment, and decision-making techniques in a representation that can be understood and manipulated by a computer that is accessible to other troubleshooters. In this manner, the knowledge and skills of the expert can be used to advise and amplify the knowledge of less experienced personnel.

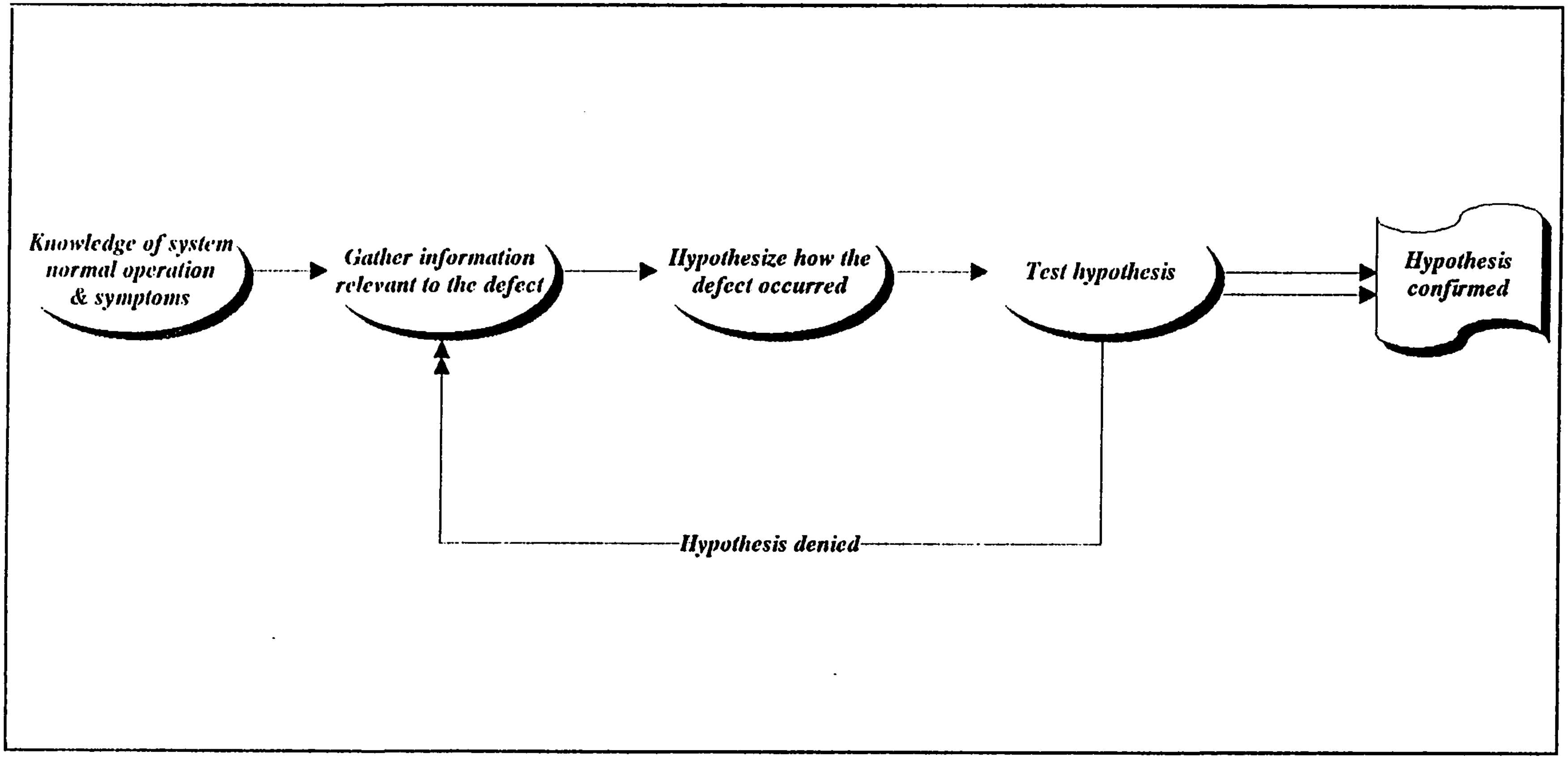


Fig 1.1 The Diagnosis Process (adapted from Rauch, Hindin, 1988)

The expert system can be the basis of systematic maintenance procedures, both preventive and corrective. The implementation of the expert system increases the chance that all alternatives and related causes and effects to the observed problem can be considered. In many cases, the observed problems are only symptoms of a larger problem which is often overlooked because maintenance personnel cannot understand or perceive a connection between different functioning parts of the building fabric. Additionally, the development of this expert system can also be a design aid in the development of new buildings and the maintenance programs to handle them.

1.3 Objectives

The overall objective of this research is to develop an expert system for structural maintenance of concrete buildings in Saudi Arabia on an IBM- Personal Computer or compatibles. The software will reflect maintenance practices implemented in the Kingdom, and will reduce the need for a large number of staff, and expertise, usually imported from outside the country. Fig 1.2 shows the study objectives of this research. The specific objectives of the intended research can be summarized into the following steps:

(1) Extracting concrete defects information; how they occur, and what the possible preventive or corrective measures are currently in use.

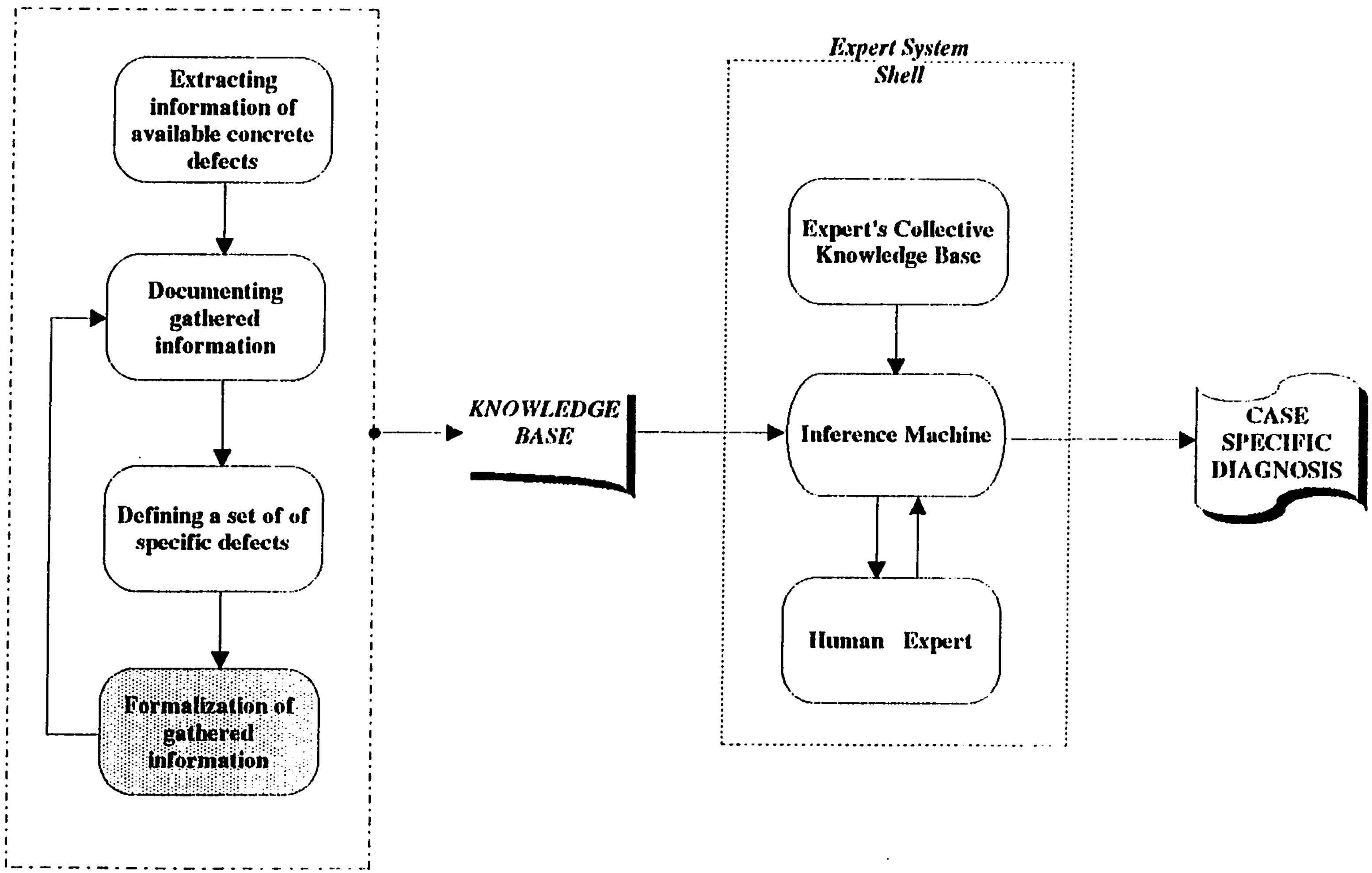


Fig 1.2 Diagram depicting study objectives

(2) Documenting available existing building problems through local field observation of building maintenance conditions and problems.

(3) Defining a specified set of building defects, as well as studying them and their related aspects.

(4) Arranging the collected information -knowledge base- in a format that can be formulated in a Rule-Based System.

(5) Implementing and demonstrating the formulated knowledge base into a diagnostic expert system.

1.4 Scope and Limitations

Due to the need to collect a huge amount of knowledge to establish the intended system, and the variety of building defects in different concrete members. The scope of this research is limited to the following:

(1) Emphasis is going to be on reinforced concrete framed buildings.

(2) Problems are going to be detected in existing buildings in view of established documented cases.

(3) Only defects of structural concrete columns, beams and slabs are going to be studied.

(4) The intended task of the system is only diagnosis of defects, repair strategies can be handled in future research.

CHAPTER 2

EXPERT SYSTEMS

2.1 Background

In many cases, common practice in the area where the site is located will guide the practitioner decision. This approach can lead to costly mistakes. A decision to adopt a specific repair strategy that is based on inexperienced judgments, would end up in incurring additional costs, delay and potential reduction in the end result quality. Relying extensively on usual practice can also lead the investigator to overlook aspects important to a particular problem.

The computer plays an important role in any engineering decision by extending the computational facilities for engineers, so that complex decisions may be thoroughly studied and approached. Traditionally, the role of the computer has been restricted to the design/analysis cycle. However, a more promising and interesting approach is to consider the role the computer may play in other less formalized phases of the engineering task. Some of the promising fields of application include: various design tasks in the preliminary design phase, selection of a piece equipment, site management, project administration, decision on a repair method, choice of a construction technique, and various more. (Maher, 1987)

Artificial Intelligence (AI) is an area in computer science and engineering that is concerned with a broad range of topics that are related to simulating human intelligence in a computing machine. Some of the better known areas of AI include machine vision, natural language understanding, speech recognition, robotics, and expert systems. Expert systems are interactive computer programs incorporating judgment, experience, rule of thumb, intuition, and other expertise to provide knowledgeable advise about a variety of tasks (Gaschnig, 1981). Many conventional programs written in structural oriented languages such as FORTRAN and PASCAL fit into this definition, yet they are not expert systems.

An expert system (Hayes - Roth et al., 1983) is a computerized problem solver containing a large heuristic knowledge base in a specific domain. It uses the knowledge to draw conclusions and emulate the performance of human experts. Stripping the knowledge base of the expert system yields a shell containing only interface and inference mechanisms, which interpret and draw conclusions when knowledge base is provided. (Yeh et al., 1991)

In the intended domain of study "*concrete diagnosis*", expert systems can be of tremendous help where qualitative and experience based knowledge has no substitute. Documenting and transferring expert knowledge efficiently to those in need of it today can have a significant impact on the state of practice. There is also a need for preserving this knowledge for new generations to use and build upon. In addition, expert systems can bring other benefits like the systematic consideration of all facts relevant to the proposed task, and the potential use of many fields and levels of expertise in solving a problem. (Santamarina, 1987)

2.2 Expert System Approach

An expert system is a computer program that attempts to model the qualitative knowledge and experience of a human expert. Expert system development tools contain two components that facilitate the creation of expert systems: a way to store the expert's qualitative knowledge used to address a given problem, and an inference control mechanism that decides how the stored knowledge will be implemented. (Waterman, 1986)

In an expert system, the knowledge needed to solve a problem is separate from the inference engine code that decides how knowledge is applied. The inference engine decides which rules are needed, regardless of their order. In procedural programs, which process code sequentially, the knowledge and controlling code become intertwined. Figures 2.1 and 2.2 depict how both types are processed on computers (Frenzel, 1987). This distinction is important when new information becomes available or

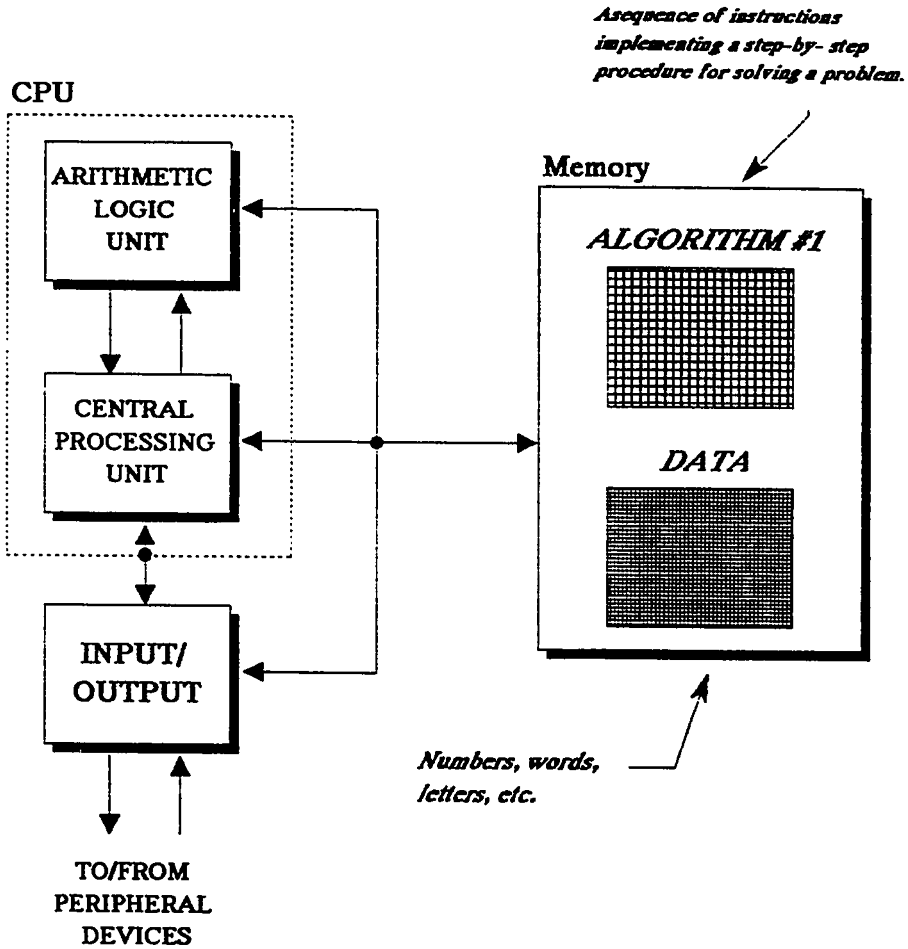


Fig 2.1 How Computer Processes Conventional Algorithmic Software
(Frenzel, 1987)

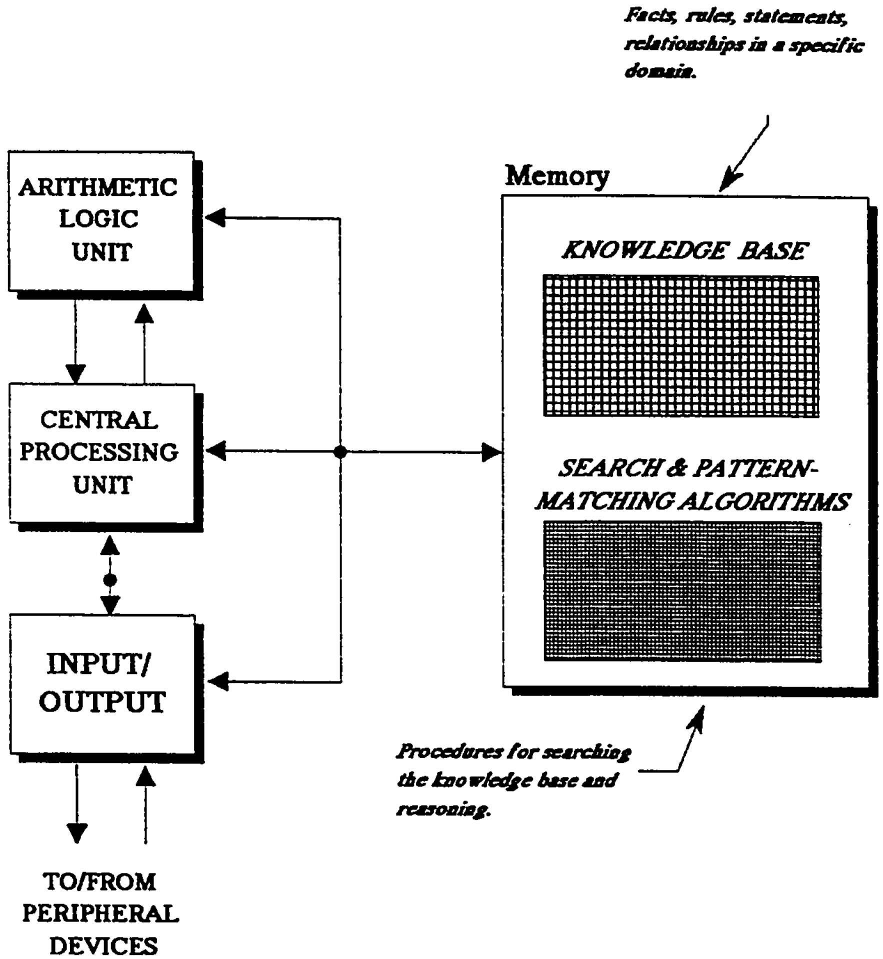


Fig 2.2 How Computer Processes Artificial Intelligence Software
(Frenzel, 1987)

conditions change. An expert system is much easier to modify and expand than a procedural program. Moreover, an expert system, as opposed to a procedural program, allows users to query the system about why a question is being asked and trace the logic that the system used to reach a conclusion. An expert system is also capable of integrating uncertain and unknown information in its conclusions. (Guru, 1989)

Table 2.1 lists the major differences between conventional programs and expert systems (Maher, 1987).

Expert systems offer a number of advantages over procedural programs:

1. Most human experts are more comfortable converting their knowledge into rules of thumb than procedural programs.
2. The modular and independent nature of rules make them easier to modify without affecting other rules. This would not be possible with a procedural program.
3. The inference engine automatically generates an audit trail of rules used. This can be used to question or verify rules.
4. Subsets of a knowledge base can be used without writing new software, due to the separation between the inference engine and the knowledge.

Besides the advantages expert systems offer over procedural programming, they furnish several benefits that encourage their use for

Conventional Programs	**Expert System**
- Representation and use of data	- Representation and use of knowledge
- Knowledge and control integrated	- Knowledge and control separated
- Algorithmic (repetitive) process	- Heuristic (inferential) process
- Effective manipulation of large data bases	- Effective manipulation of large knowledge bases
- Programmer must ensure uniqueness and completeness	- Knowledge engineer inevitably relaxes uniqueness and completeness restraint
- Impossible midrun explanation	- desirable and achievable midrun explanation
- Oriented toward numerical processing	- Oriented toward symbolic processing

Table 2.1 Differences Between Conventional Programs and Expert Systems (Maher, 1987).

knowledge handling:

1. Expertise can be saved. Employees near retirement can leave a model of their specialized knowledge about a product, piece of equipment, or a problem. Their expertise is then always available for others to consult.
2. Expertise can be standardized. Uniform decision-making can be applied to similar situations.
3. Expertise can be distributed. Remote offices can make use of one expert's knowledge.
4. Expertise can be combined. Several experts can combine their rules in one system, creating a powerful consulting tool.

While considering a certain domain to build an expert system, the problem domain should be carefully studied to know whether it is suitable to be best handled by following expert system approach. Certain domains suit expert systems; many other do not. (Maher, 1987; Waterman, 1986) Table 2.2 compares domains where expert systems are applicable to those where knowledge can better be represented through adopting conventional programs.

Suitable Problems	Not Suitable Problems
- Where judgment and subjective evaluation is involved.	- Procedural problems, involving step by step solutions
- Where human expertise is clearly identifiable	- Where human expertise does not exist
- Which can be solved in relatively short time	- Trivial or too complicated problems
- Where human expertise is not readily available or affordable	- Where human expertise is abundant and inexpensive

Table 2.2 Suitability of Problems Characteristics to adopt Expert Systems Approach (Guru, 1989)

2.3 Expert Systems in Building Maintenance:
A Diagnosis System.

Building maintenance is certainly a diagnosis problem in nature. It is particularly attractive and ready to be distilled into a decision support system. This is true since: it is a well defined domain, the selection of repair methods is well determined by the job characteristics and the required performance, documented cases exist, and qualitative variables enter the decision process.

Diagnosis involves the investigation of the cause of a fault in a system. The diagnostic process is unusual among intelligent human activities in that it is understood well enough to build knowledge-based systems that leverage troubleshooters of all sorts of problems. It is therefore no surprise that diagnostic knowledge systems are the most common AI systems in use today (Rauch, 1988).

To perform the diagnosis function, expert systems use descriptive situations, behavior characteristics, or knowledge about component design to infer probable causes of system malfunctions. Examples include the following:

1. Determining the causes of diseases from symptoms observed in patients.
2. Locating faults in electrical circuits.
3. Finding defective components in the coolant systems of nuclear

reactors.

4. Diagnosing the causes of building deterioration and suggesting corrective actions.

When a concrete structure experiences a damage or more worse a failure, the need for systematic diagnosis of the causes of damage is very important to pinpoint the causes, expose defected locations and propose corrective actions. Unfortunately, there is no single algorithm or instrument that can discover all damage causes. Moreover, the inference should be based largely on the knowledge of human experts. Usually, human experts judge the damage causes with heuristics rather than algorithms. In general, a *heuristic* is a proposition (rule or relation) that consists of antecedents (evidences, damage symptoms) and consequents (hypotheses, damage causes).

Depending on its **knowledge representation,** the expert system might provide a series of questions about the characteristic and nature of the maintenance problem. The user answers those questions. He might be asked to conduct certain tests to further define the problem. The expert system can then identify the type(s) and reason(s) of the defect, and the possible corrective action(s).

Expert systems performing diagnosis do not only define defects, but also assist with debugging. They may interact with the user to help find the faults and then suggest the course of action to correct them. (Waterman, 1986).

2.4 Previous Work

Search in the literature revealed that the practice of expert systems implementation has received intensive attention over the last decade. As a result, several researches concentrated on adopting expert system approach to solve complex engineering and management problems. Areas of potential application in construction were found to include interpretation of design codes, building and planning regulations, preliminary design, project time and cost control, building repairs, and tender evaluation (Expert, 1986).

The use of expert system in the field of diagnosis specifically has received quite attention. Some diagnostic knowledge systems have already demonstrated payback. For example, *Spear*, a remote tape-drive diagnostic system that contains an AI component, saves Digital Equipment Corp. $50 million a year. *Spear* is usually run periodically for preventive maintenance. During system execution, it calls the remote system and reads its error logs. The AI component uses the error data and its own knowledge to detect causes of intermittent failures and to predict hard failures before they occur. In the case of an existing failure, *Spear* determines, in advance, the bad component and then dispatches a repairman. (Rauch, 1988)

Some of the expert systems that have been built to perform diagnosis are summarized hereafter: (Table 2.3)

Expert system	Domain	Source of knowledge	Development tool	Structure	Features	Year
REPCON	Building repairs.	Personal experience. Structured lectures. Published literature.	commercial tool + Pascal.	Production rules.	Uses checklist proformae, metaknowledge and external graphics.	1990
DURCON	Design of concrete in aggressive environment.	ACI 201.	Pascal.	Rule-based.	Uses simulation models, databases, and bulletin boards.	1985
WADI	Preliminary diagnosis of failure of retaining walls.	Published literature.	TOPSI tool.	Rule-based.	Uses inspection database.	1987
SPERIL-1 *SPERIL-2* *SPERIL-3*	Damage assessment of existing structures.	Visual inspection. Earthquake records. Laboratory data.	C. Prolog. Lisp.	Rule-based. Rule-based. Frames.	Uses linguistic assessment, fuzzy sets, two phases consultants.	1980/83 1983/84 1985
DAPS	Structural damage assessment of buried box culverts.	11 test experiments. questionnaires.	EXSYS.	Rule-based.	Uses numeric and non-numeric information, fuzzy sets, and linguistic damage descriptors.	1990
IMPROVE	Selection of soil improvement methods.	50 case histories. Literature expertise.	Unknown.	Rule-based.	Uses windows, best search algorithm, and case histories database.	1989
PCPILE	Diagnosing damage of prestressed concrete pile during driving.	Published material. Experts' experience. Case records.	Turbo Prolog.	Production rules.	Case based and uses analogical inference technique.	1989
KEBS	Diagnosing damage of prestressed concrete pile during driving.	Inductive learning by questionnaires, past records, and simulation.	Prolog.	Rule-based.	Uses inductive learning algorithm and decision trees and training examples.	1990
DEX	Design of durable concrete.	BRE digest. Concrete experts.	CRYSTAL.	Production rules.	Uses hypertext techniques, and blackboard architecture.	1991

Table 2.3 Summary of Developed Systems Handling Concrete Diagnosis and Repair

REPCON. (An Expert System for Building Repairs)

REPCON was intended to assist building repair consultants and maintenance engineers in their daily tasks to define and diagnose building defects and then propose a corrective action. It is a prototype expert system that attempts to capture a wide body of knowledge in building defects. It is based on - so called - knowledge nets pertaining to various building defects, which are formed into rule bases. The ES's metaknowledge base is used in a unique way to guide the user in the diagnostic process by means of checklists called "proformae". Externally activated graphics programs have been used to help the users to identify crack patterns. (Kalyanasundaram, 1990)

the system evolved through the effort of a group consisting of a domain expert and two knowledge engineers. The information collected to form the knowledge nets was based on the personal experience and structured lecture courses given by the domain expert, supplemented by published literature available in books and journals on the subject. *REPCON* was developed on an IBM PC/AT using a commercially available expert system development tool and Pascal programming language. the system has 645 rules, and the development tool limits maximum possible incorporation of rules to 750 rules. (Kalyanasundaram, 1990)

DURCON.

It is a system developed by Clifton et al (1985). ***DUR*ABLE**

*CON*CRETE is a prototype expert system for selecting the constituents of concrete exposed to aggressive environment. It addresses the deterioration of concrete to four factors; i.e. freeze-thaw, sulfate attack, corrosion of reinforcement, and cement-aggregate reactions. The knowledge base consists of specification rules from the ACI Guide to Durable Concrete (ACI 1977), and makes use of heuristic knowledge obtained from human experts on concrete durability. *DURCON* is a rule-based system developed in Pascal on an IBM PC using the forward chaining mechanism. An example of the rules used in *DURCON* is :

IF	Severe freeze-thaw conditions are anticipated	**AND**
	The nominal size of aggregate is 3/8 in	
THEN	The percentage of entrained air should be 7.5	

WADI.

Chahine and Janson (1987) describe the implementation of an expert system built in TOPSI for the preliminary diagnosis of the failure of retaining walls. TOPSI is a rule-based ES environment implemented in Turbo Pascal. *WADI* is applicable to two types of retaining walls: cantilever reinforced concrete walls and gravity concrete. Domain expertise was mostly obtained from books and journal articles. It obtains the description and the characteristics of the retaining wall, the characteristics of the backfill and bearing soils, and data describing the failure symptoms from an inspection database which includes information collected during field inspection. *WADI* then generates all the potential problems: the footing problem, the drainage problem, the construction problem, and weak soil bearing. It proceeds with performing stability analysis and related factors of safety and compared to allowable. Conclusions are finally made explaining the potential causes of failure and recommending remedial actions.

Expert System for Condition Survey of Existing Structures.

SPERIL (Structural PERIL) are expert systems for damage assessment of existing structures, being developed since 1980. In *SPERIL -1* (Ishizuka et al., 1980-83), an arbitrary measure was used. The program portion was written in C language. In *SPERIL-2* (Ogawa et al., 1983-84), a more structured mathematical integer was used as a measure of structural safety. In addition, logic is used to represent rules, facts and available data on the existing structure, as well as control the inference to obtain conclusions. The program in *SPERIL-2* was written in PROLOG. A new version, *SPERIL-3,* was developed later on the basis of a preliminary version called **CES-1** (Civil Engineering System), which consists of four parts: inference machine, knowledge base, memory and learning machine (Zhang, 1985). A frame structure was used to represent knowledge in **CES-1**, and the program was written in LISP.

SPERIL-1 and *2* are basically rule- based systems, **CES-1** adopts frame as a knowledge representation technique. Knowledge in *SPERIL-3* is classified into several different categories and is represented by using frame-like structures. Available information in **CES-1** is classified into several categories such as general knowledge, inspection information, loading condition, and accelerometer records. The order of these questions is ranked according to the degree of difficulty in obtaining such information. **CES-1** starts by asking for general information which is useful for consultation purposes. For example, a question about the purpose of assessment is asked. If the answer is "damage assessment after an earthquake", the slot of earthquake information is filled. Therefore the frames corresponding to earthquake are taken and questions about the particular earthquake will be asked. Otherwise, no question about earthquake records will be asked. In this manner, only relevant questions will be asked. The machine then calls for the category of questions pertaining to the situation. If the results are still not sufficient for determining the structural condition, a suggestion is made that the user should collect more information concerning the unanswered categories of questions.

Based on **CES-1**, the consultant process of ***SPERIL-3*** was designed in a hierarchical fashion. Two phases of consultants are used to obtain a good assessment of the structural damage and to keep the cost of the assessment low. Phase I, generates questions to cover general information, design quality, construction quality and feelings resulting from visual inspection. On the basis of each type of information, suggestions may be made such as "no action is needed", "laboratory tests are required", "loading tests are required". In phase II, more detailed information is to be requested and a decision is made according to the input information.

DAPS.

It is a rule-based expert system incorporating the framework for Structural Damage Assessment of buried box culverts. An analysis of the structural integrity of a buried concrete box culvert is accomplished using combined numeric and non numeric information. ***DAPS*** includes the available information about damage, whether it is expert opinion, engineering judgment, digital wave forms, etc., and retrieval strategy of this information. It combines numeric as well as non numeric information and is based on the theory of fuzzy sets in order to quantify, combine, and interpret linguistic damage descriptors. (Ross et al, 1990)

The work is part of a project for the United Air Force aimed to improve the methods and procedures used to manage the huge information generated from field testing. The database used includes a series of 11 experimental tests that were performed on buried reinforced concrete boxes subjected to explosive-type pressure loading. The knowledge base for ***DAPS*** is comprised of numeric information in the form of measurements that were obtained from the experimental tests and information in the form of linguistic data that were gathered from professional experts through questionnaires related to the 11 tests. The damage assessment paradigm is subdivided into smaller problems, which in turn are represented in antecedent-consequent pairs of rules. These rules and numerical data form the knowledge base. Numeric data are manipulated in the expert system through calls to external subroutines and data bases. This information is then interpreted through the use of production rules.

The major factors (modules) influencing an assessment procedure in ***DAPS*** include structural integrity, functionality, and reparability. The ultimate goal, therefore, was set to take the assessment of each of these factors and combine them into one total meaningful assessment. The output of the overall structural integrity module, for example, provides the user with the most likely mode of damage and a linguistic assessment of that damage. Achievement of the overall goal in damage assessment through combining results produced from each of the three modules is still under continuing research. (Ross et al, 1990)

IMPROVE.

It is a decision support system for the selection of soil improvement methods. The system uses a knowledge representation structure based on windows, together with a best search algorithm. This form of representation has many advantages and allows for procedures not available in other systems, such as the development of composite solutions, the use of different evaluation functions, the search for lacunae, and the case-based representation of knowledge. (Chameau et al., 1989)

The system consists of four parts: preprocessor, selection of methods, selection of similar cases, and postprocessor. The *preprocessor* helps the user decide whether a soil improvement technique is necessary, based on a single stack of windows. Then comes the second module, where more than 40 methods exist in the database. The search of the stacks of each method starts with the information that was provided during preprocessing, and ends with the selection of the best alternative.

In the third module, the search algorithm selects case histories that best resemble the project under-study. ***Improve*** contains 50 case histories where soil improvement methods were successfully adopted and can be potential alternatives for the studied project. Finally, the ***postprocessor***, being a rule-based system, provides final information and suggestions on design and construction guidelines for the selected improvement techniques. (Chameau et al., 1989)

PCPILE.

*P*restress *C*oncrete *P*ile is a diagnosis expert system for diagnosing the damage of PCP during the construction process. The inference is mainly implemented by the deductive inference mechanism with depth-first backward chaining. Yet, when this mechanism can not satisfy a diagnosis directly, a specific case base is opened for the analogical influence mechanism. (Yeh et al., 1991)

The system is built in Turbo Prolog, it contains about 80 rules and 100 cases. In the knowledge base, one case base is regarded as one macro goal in one rule, and rules are classified into rules without case base and rules with case base. The former are processed first in the knowledge base. Therefore, inference process is preceded by depth-first backward chaining deductive inference on the rule base. After all rules without case bases are tried or failed, the system proceeds to search the rest of the rules, and the analogical inference mechanism will be activated to implement the case matching procedure. (Yeh et al., 1991)

2.4.1 Critique

Although, as noted above, work has already been carried out on the application of expert system techniques to concrete diagnosis with diversified approach and handling of problems, it is not of direct use in the Kingdom nor in the Gulf states. All of the systems were based on building standards and experimental results that may not be applicable here. It is crucial to base a system on the building standards and experience commonly practiced in the region. Moreover, the published descriptions of the mentioned systems do not depict clearly how they address some of the issues in the diagnosis of existing structures. Furthermore, among the reviewed systems no single one addressed the problem of proper identification of deterioration inhibitors. A clear example of this fact is that all of the systems either try to assess the degree of damage or recommend a repair technique without a thorough investigation of the real cause of deterioration. Identifying the exact damage cause is mandatory to any diagnosis, not to mention its importance in setting preventive maintenance programs, and design of durable structures.

CHAPTER 3

CONCRETE DIAGNOSIS

3.1 Concrete Building Problems

Cracks in concrete have many causes. They may affect appearance only, or they may indicate significant structural distress or lack of durability. Cracks may represent the total extent of the damage, or they may point to problems of a greater magnitude. Their significance depends on the type of structure, as well as the nature of the distress. (ACI 224-84) Buildings may be effected by various causes such as foundation movement, structural deformation under loads, expansions or contraction due to changes in temperature, corrosion of reinforcement, dampness, improper design and detailing, and inadequate quality control. Buildings may also be damaged by other causes such as floods, fire, vibrations and earthquakes. Under the influence of one or more such causes, a building may suffer partial or full damage. While the causes for total damage are specific and can easily be identified, the causes for partial damage can be several and therefore are difficult to identify. (Kalyanasundaram et al., 1990)

There are several methods available for evaluating concrete properties in existing structures. The aim is to assess quality and identify any source of detrimental effect on the concrete performance as to reduce its strength or deteriorate its integrity. However, general knowledge of the structural design criteria and the various structural elements existing in a structure is a key to determine where the exact defected or inactive member and/or harming agent is located. This is a crucial step in any effort or procedure undertaken to diagnose a structure. (ACI 207-79)

Consequently, in this study the major structural elements (*columns, beams, slabs*) have been separated, and each is investigated as a unit by itself. The aim at isolating them from the rest of the structure, is to study the causes of deterioration a specific element may exhibit due to whatever harming agent. An example, can be sulfates or poor construction practice or any other deteriorating action that may or has already offset the structural integrity. That action may ultimately end up causing that element not to perform or sustain imposed loads or not functioning under existing service conditions.

This method is adopted to fulfill the objective of this study as to understand the basic defects of each separate member. Then, trace down these defects to most basic part or location of a member. The method facilitates proper identification of each defect, associating it with its best indicative symptom, and studying its basic major and/or minor causes. The objective was to set required checks and tests as well as any further procedure needed to furnish a solid ground for the diagnosis process.

3.2 Investigation and Evaluation of Concrete

The most difficult and important step of any intended repair process is determining the cause of degradation. It is not possible to evaluate the need for repair or select a repair procedure with assurance of satisfactory results unless the cause is understood. Causes of concrete deterioration can not often be identified, either because insufficient data are available to expose the problem, or because the simultaneous action of several agents. (Mailvaganam, 1992)

The need of a careful and thorough evaluation of the existing condition becomes essential prior to planning any repair work. The purpose of an investigation should be collection of information, identifying the extent of deterioration, and establishment of the cause and significance of such deterioration. This evaluation can only be accomplished through a systematic review of service records and the original design and construction details of the structure. A detailed field investigation is to be planned to follow the review of the documents. Intelligent observation and sound judgment are inevitable tools to overcome the dilemma of unavailability or lack of records. An investigation program should include visual examination, nondestructive testing, and collection of specimens for laboratory testing. (Perkins, 1986; Mays, et al., 1992)

The results of the field investigation and laboratory testing will have a significant bearing on the selection of repair materials and methods of repair. Usually, services of specialists in material testing and structural design are inevitable to undertake such investigation task. Pollock proposed a detailed flowchart that illustrates the diagnosis process, such as the one in Fig 3.1.

3.2.1 Condition Survey

Condition survey may range to cover a cursory visual assessment to a complex operation that involves time intensive planning and execution. However, in all cases, the prime objective is to identify the possible causes of any visible distress and to establish the structural integrity and satisfactory performance of the structure. (ACI 201-79, Fookes, 1981)

A problem's simplicity and the experience of the engineer plays a vital role to drive recommendations for rehabilitation, being based only on a cursory visual assessment. Therefore, at an early stage of planning a survey, a team effort becomes a necessity. It is important to have a full understanding of the structural performance and materials properties; and after a thorough review of the factors an engineering judgment can be approached. That is why a high need arises to combine and arrange this team effort in an expert system. This would facilitate a proper and comprehensive assessment and help the decision making process arriving at an assured diagnosis.

Five main tasks constitute survey activities; namely: collection of information, establishment of in-service conditions, field visit, detailed

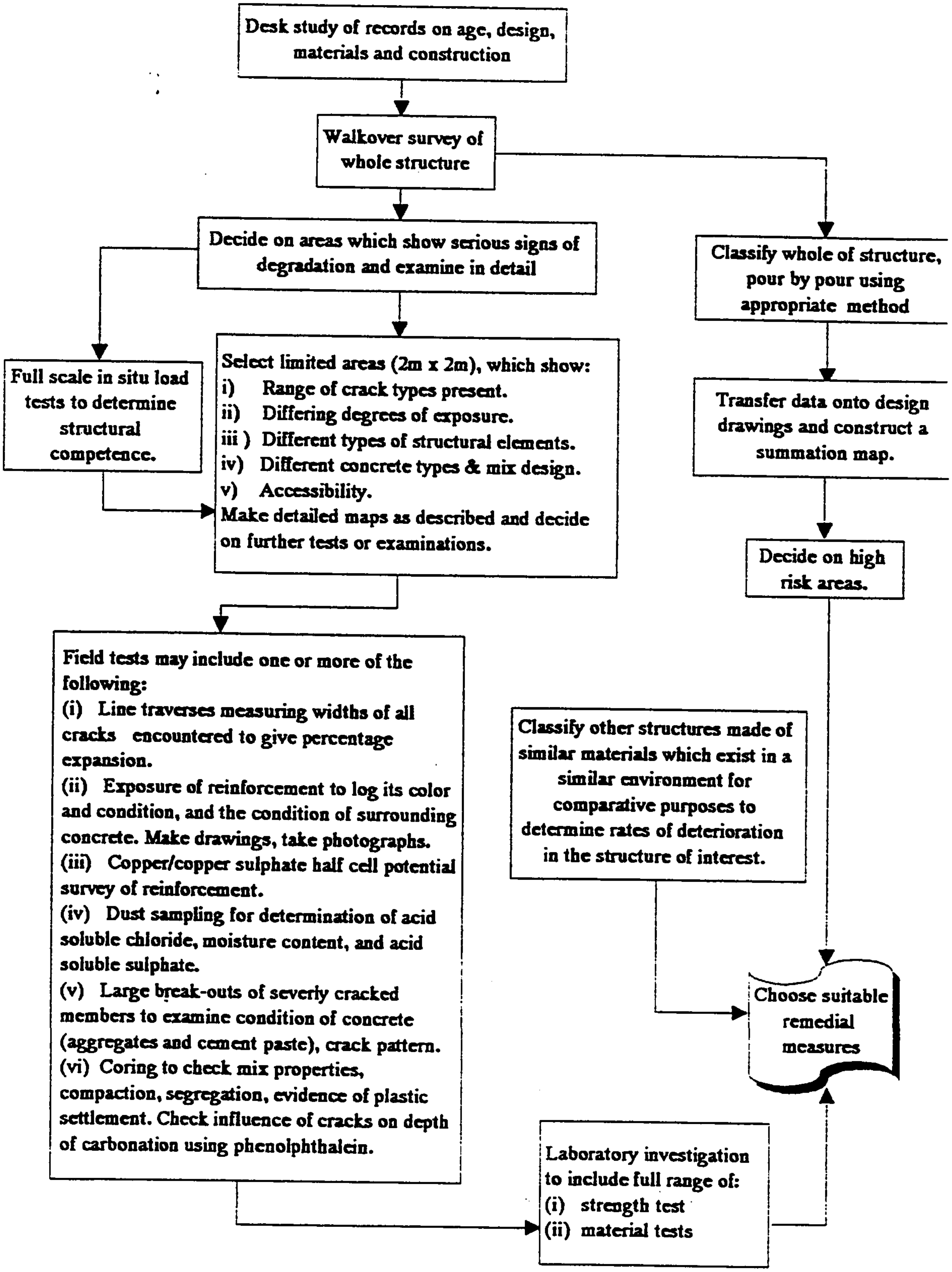


Fig 3.1 Flow chart to outline investigations of deteriorated concrete *(after Pollock et al., 1981)*

survey, and evaluation of data. (Mailvaganam, 1992)

A. Collection of Information

This task involves collection of all available information on the structure. A suggested brief list of the required information follows:

- Specifications.
- Drawings.
- Construction records.
- Photographs.
- Post construction reports.
- Test reports on materials.
- Unusual events during the construction period.
- Presence of instrumentation to monitor structural performance.
- Baseline data from such instrumentation.
- Previous repair works.
- Recent photographs of critical locations.
- Names of involved parties.

Once all the pertinent data are collected, a detailed review is carried out and a checklist is prepared. The checklist should include all data which are required for an in-depth evaluation. The (ACI 201-68) and (ACI 311-80), Appendix A.1.(a and b) recommend a baseline checklist which cover different aspects of the structure. The items in a list may change according to the type of structure being investigated.

Careful consideration of the obtained information will often indicate possible underlying causes of deterioration and help in drawing up proposals for the detailed investigation, sampling and testing. (Perkins, 1986)

B. Establishment of In-Service Conditions

This task forms the procedures followed for ascertaining how the structural components are functioning under in-service conditions. Once a preliminary assessment of the design function of the structural components of the building is made, the following items should be identified:

- Areas of high stress.
- Areas exposed to factors such as temperature and humidity, etc.
- Existing service conditions, i.e., overloaded areas.

C. The Field Visit

The ground is now solid for planning an initial site visit. During which specific and detailed notes are made, such as crack mapping as well as any other sketches and plans on the existing condition of the structure. (Pollock et al., 1981) During the site visit a list of activities should be completed, which covers the following: (Mailvaganam, 1992)

- Observation of visual condition.
- Photographic records.

- Condition of the areas of high stress.
- Condition of exposed areas.
- Cracks and locations of deteriorated concrete.
- Limited measurements of cracks and concrete degradation.
- Accessibility of the member for in-situ testing.

The notes and comments on the site survey should be well documented and registered. Appendix A.2 depicts an adapted general survey report that can be used as a basis for the site visit. Such a preliminary assessment provides the engineer with information that can facilitate a decision to conduct a more detailed investigation. The aim is to identify areas of most concern and to establish the requirements for a more detailed survey.

For the sake of proper established evaluation of a concrete structure, normally usual inspection can often provide valuable information. Existing features may be related to factors as workmanship, structural serviceability and/or material deterioration. It is crucial for example to differentiate between various types of existing cracks; segregation or excessive bleeding at joints may reflect problems with the concrete mix, as might plastic shrinkage cracking, whilst honeycombing may be an indication of low caliper workmanship. Lack of structural adequacy is usually shown by excessive deflection or flexural cracking. Long term creep deflections, thermal or structural movements may cause distortion of door frames or cracking around windows. To sum up visual comparison of similar members is of great value that it should precede testing to determine the extent of the existing defect. (Mays, 1992)

In general a careful preliminary visual inspection should be followed, and usually may be conducted in a manner as depicted in Table 3.1 (BRE, 1977). This table presents general questions that might be asked by an investigating-well-trained eye, in order to establish a proper identification and adequate knowledge about a particular problem. In all cases a planned approach to the investigation is worthwhile; such an approach is outlined in Fig 3.2 which refers to only cracking and spalling of concrete and not to chemical deterioration of concrete. (BRE, 1977)

D. The Detailed Survey

A detailed survey should include nondestructive tests, a detailed sampling program, measurements of structural components, mapping of cracks, installation of instrumentation to monitor movements of cracks or movement of targeted structural components. At this stage, a list of all tests required to be done on the structural member should be drawn up (Mailvaganam, 1992; Bungey, 1982). In case cores are obtained, proper identification should be followed, and a list of required tests on the core must be reported on each core.

E. Evaluation of Data

A detailed evaluation of the field and laboratory test data, including

Table 3.1 Sample Listing of General Checks Adopted to Facilitate the Diagnosis Process (*BRE, 1977*)

Evidence	Tests
Thermal movement	Does it appear greater on S-facing than N-facing walls? Does its timing match temperature changes (diurnal, seasonal)? Is it greater in dark-colored components than in similar light-colored? Does its magnitude match expected values for thermal movements? (Caution: restraints may modify movements in practice).
Moisture movement	Are the concerned materials susceptible?
Sulphate attack	Are all three ingredients present? (Cement, sulphate salts, persistent dampness). Is expansion of the member taking place?
Corrosion of reinforcement	Is reinforcement present near cracks? Could the concrete contain chlorides? Does cracking follow a linear pattern?
Rain penetration	Could it be partly or wholly condensation? Could it be rising dampness?
Cracking due to any supposed cause	Diagnosing the cause of a crack is established by raising the following questions: Does a straight edge, applied across the crack, reveal misalignment of the faces? (may indicate lateral displacement of one part and thus the direction of movement). Is the crack of approximately constant width throughout its length or is it tapered; if so, in which direction? (taper indicate hogging or sagging). Does the crack close to short returns? (may indicate rotation of returns and thus the direction of movement). Is the crack accompanied by spalling? (may indicate compression). Is the line of the crack at an angle? (may indicate shear forces) Is there evidence of the age of the crack? Is there evidence of time of occurrence? In all cases, look for confirmatory evidence provided by repetition in other similar locations.

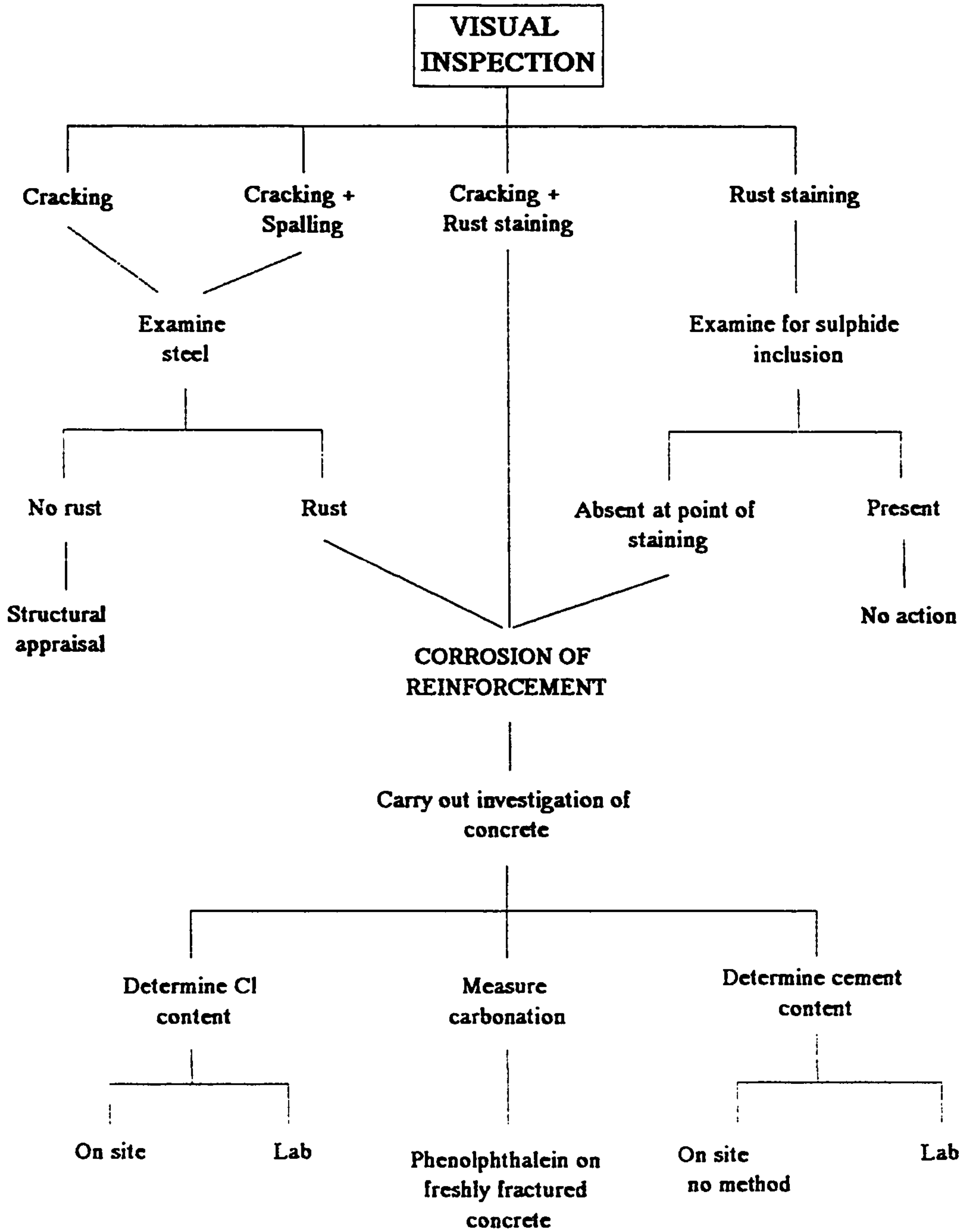


Fig 3.2 A Typical Inspection Flowchart That Refers to Reinforcement Corrosion *(BRE, 1977)*

the relevant observations and notes made during the condition survey, should be performed. (ACI 207-79) The level of the survey is established by the way in which the information on the condition of the structure is to be used, and this in turn controls the details to which the inspection and/or testing is carried out. Eventually, a proper rational evaluation of the structural condition can be accomplished. (Rewert, 1985)

3.3 Types of Defects

During the detailed survey, an investigator should be fully aware of the different manifestation of different problems, and how to differentiate between variant types of cracks and other existing symptoms. A reasonable assessment of the cause of a defect can only be made on the basis of the information obtained, plus the study of project drawings, specification, reports and other available documents. Observations of patterns of cracking, seepage, discoloration, staining, spalling, softening or erosion of the surface can give valuable indications of the possible cause of damage. However, caution is required, because the same physical effects may be produced by different phenomena.

In the Middle East, due to the combination of aggressive ground conditions, material and climatic factors, cracks tend to propagate and progress more rapidly. Some of the cracks related to forms of deterioration common in the Middle East are summarized in Table 3.2 and

Fig 3.3. (Pollock, 1981)

Several classification of cracks exist; they differ according to the nature of classification. According to their behavior, cracks are categorized into progressive and non-progressive. *Non-progressive* cracks are those which once formed do not continue to develop unless an agency other than original cause is also present. *Progressive* cracks, on the contrary, continue without any other cause than the reason for the initial cracking. Examples are structural distress, corrosion related cracking, and alkali reactivity, etc. (Pollock, 1981)

Non-progressive cracks in the Middle East allow air, moisture and soluble salts to penetrate the concrete and hence a different mechanism then takes over. Such a process if allowed, would undoubtedly inhibit the ingress of undesirable material into the concrete mass. Eventually, the performance of the concrete member is endangered. The deficiencies most common in Middle East concrete along with their contributing agents are shown in Table 3.3. (Pollock, 1981) Appendix-B includes several plates that illustrate some of the concrete problems experienced in Saudi Arabia.

A. Drying Shrinkage

Drying shrinkage is caused by quick loss of moisture from the cement paste. If shrinkage is restrained, tensile stresses develop and cracking may result. Cracks due to restrained shrinkage are often noticed

Table 3.2 A preliminary table of observations and comment on various crack types in Middle East (*Fookes, 1976*)

Type of cracking	Age	Principal cause	Principal location and frequency	Principal confirmatory tests	Potential risks
(1) Drying shrinkage cracks.	Days to months.	Shrinkage from loss of moisture.	Central position walls, columns, beams and floors. common.	Coring & inspection. Timing of crack development.	Exposure of reinforcing steel.
(2) Thermal cracks.	Days to weeks for initial movement. months to year for diurnal movement.	Short & long term expansion and contraction movements.	Thin members in particular. Fairly common.	Ditto plus microscopic examination.	Exposure & Loss of bond strength to steel.
(3) Tensile cracks.	Ditto.	Tensile stress movements.	Structural members. Not too common.	As (1) but coring may be risk to integrity.	As (1) critical depending on situation.
(4) Shear cracks.	Ditto.	Shear stress movements.	Ditto.	Ditto.	Ditto.
(5) Reinforcement corrosion cracks.	Many months to many years.	Expansion of reinforcement by rusting.	Reflects pattern of reinforcement. very common.	Coring & samples for chemical tests. Observation of steel condition.	Ditto.
(6) Popouts and map cracking, plus extruded gel (alkali-aggressive).	Few months to many years	Expansion of reactive aggregates.	Any concrete. Rare.	Coring & Hand sampling. Chemical tests. Microscope examination.	As (2), but can lead to complete loss of structure.
(7) Chemical sulphate attack.	Years to many years	Sulphate salts.	From just above ground water table to well below. Not too common.	Observation plus coring & hand samples and chemical tests.	May cause eventual collapse of foundations.
(8) Floor Heave.	Months to many years.	Sulphate under floor. Dampness	Concrete floors. Locally common.	Observation plus hand samples & chemical tests.	Irregular surface.

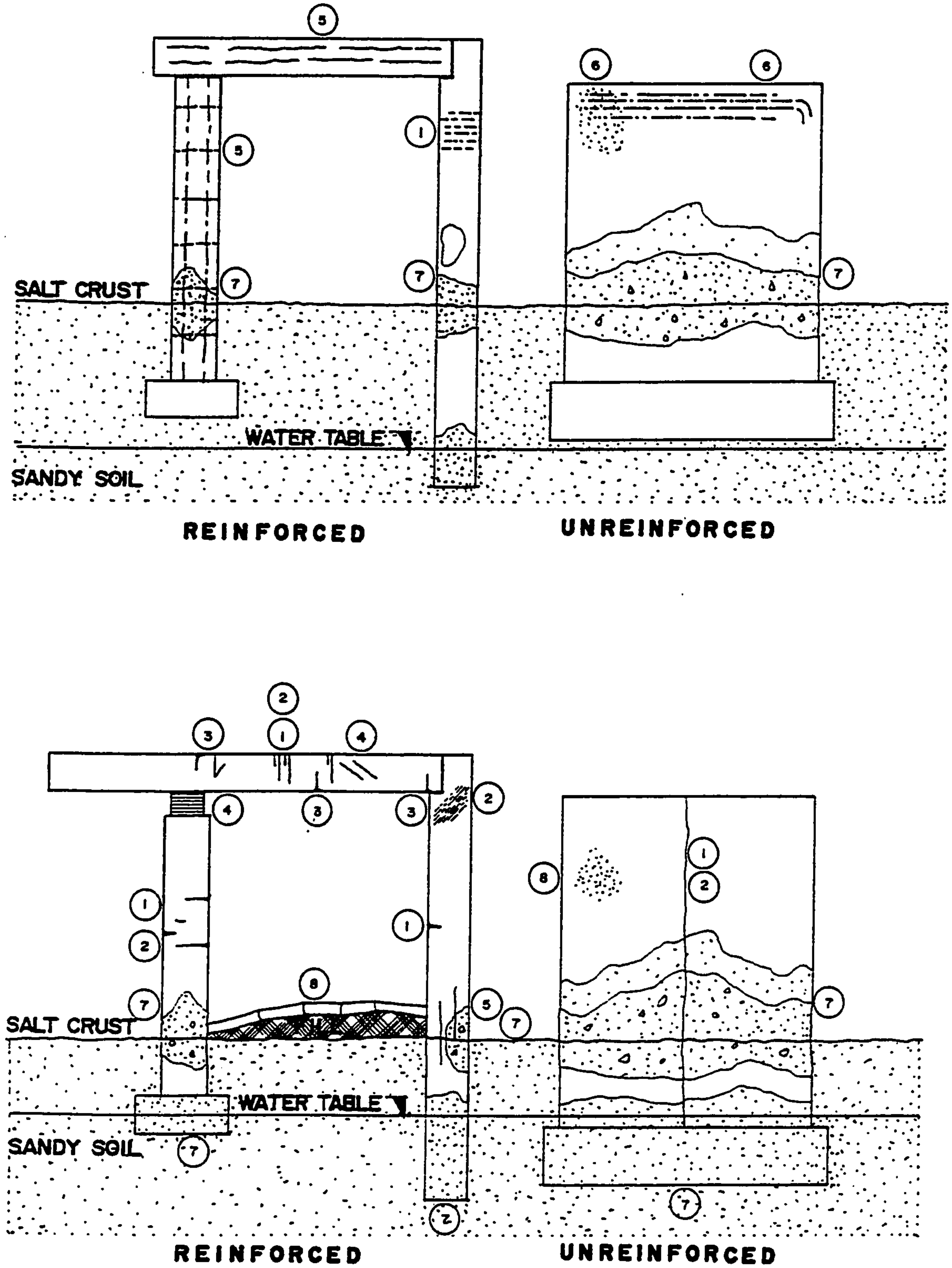
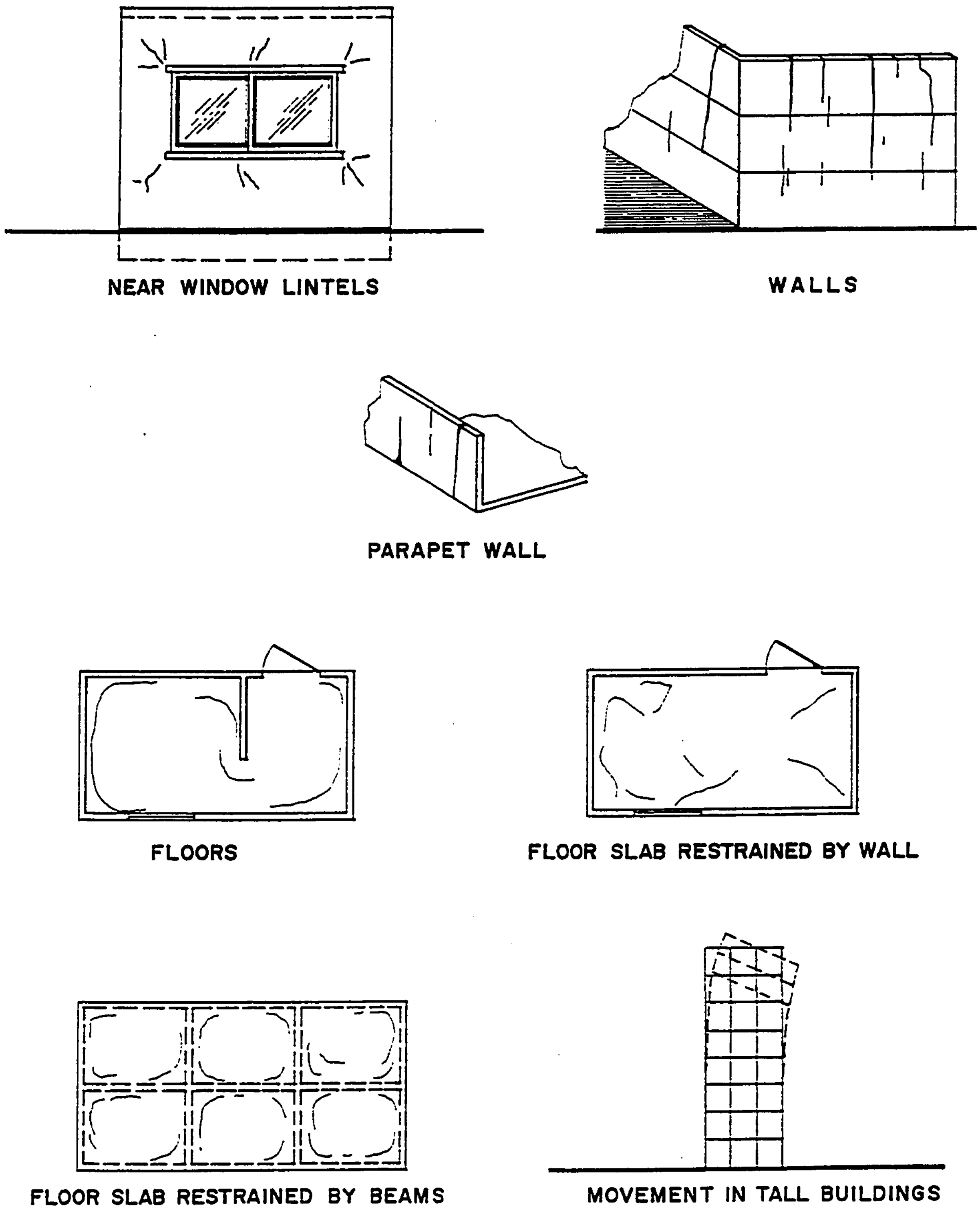
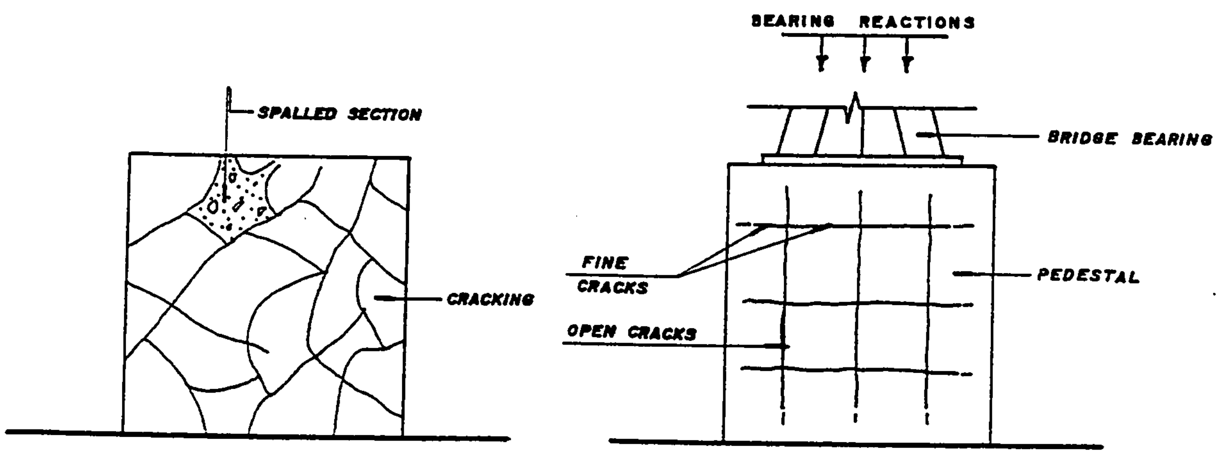


FIG. 3.3a - A HIGHLY IDEALISED ILLUSTRATION OF THE VARIOUS CRACK TYPES OUTLINED IN TABLE 3.2. CRACK TYPE NUMBER RELATES TO THE TABLE. (FOOKES , 1976)



THERMAL CRACKS

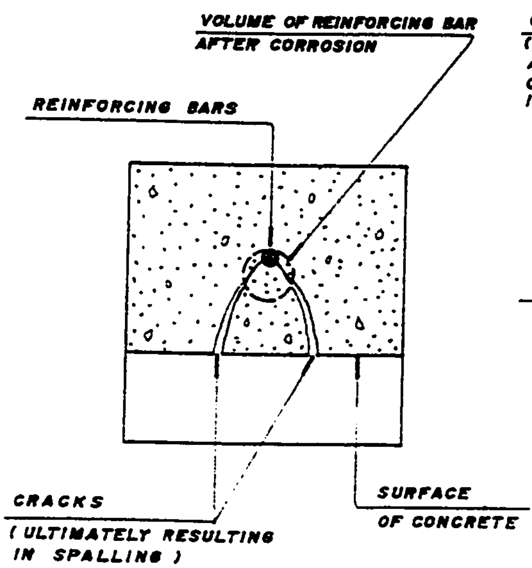
FIG. 3.3b - EXAMPLES OF THERMAL CRACKS. (FOOKES , 1976)

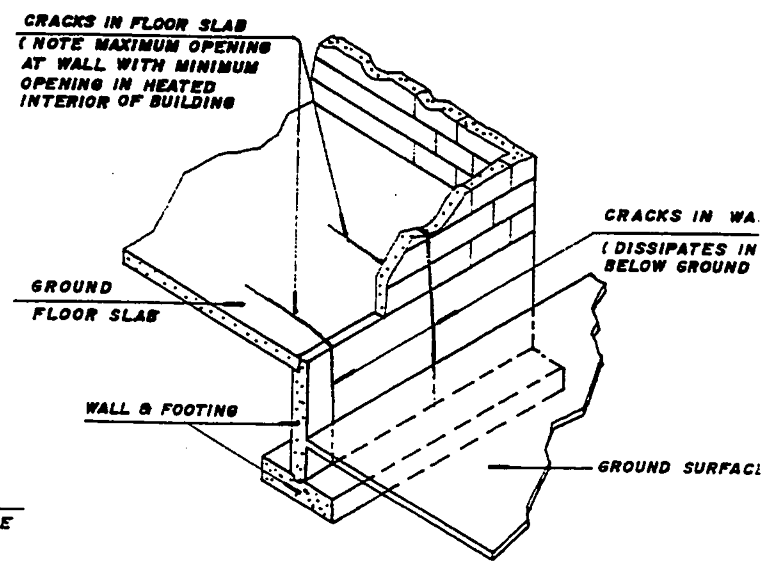


MOVEMENT UNRESTRAINED

MOVEMENT RESTRAINED ON VERTICAL AXIS

INTERNAL SWELLING





REINFORCEMENT CORROSION

THERMAL CRACKING

FIG. 3.3c - SOME DETAIL OF VARIOUS CRACK TYPES. (FOOKES , 1976)

Table 3.3 Common defects in Middle East concrete and frequent contributory factors (*Pollock, Fookes, 1981*)

Defect	Major contributing factors
Uncontrolled drying shrinkage cracks	Design- failure to provide sufficient reinforcement, inappropriate pour layout Workmanship- over-wet concrete, poor curing Climate- High mix temperatures Materials- High shrinkage aggregates
Structural distress	Design Workmanship- failure of concrete to gain specified strength
Thermal cracks	Climate- high daily and seasonal temperature range
Corrosion of reinforcement	Materials- salty aggregates Environment- contamination of stored materials, ingress of chlorides after construction Workmanship- salt water for curing
External sulphate attack	Environment Mix design- low strength, porous concrete, wrong cement type
Internal sulphate attack	Materials- aggregates containing sulphates Environment- contamination of stored materials
Alkali reactivity	Materials- reactive aggregates, cement chemistry

soon after construction, but where slow drying occurs they may not be apparent until much later. The cracks formed can vary from fine hairlines to as wide as 3 mm, and often serves as ports of entry for moisture, carbon dioxide, and other deleterious salts. Surface crazing on slabs is an example of drying shrinkage, when the surface layer of concrete has a higher water content than the interior. The result is a series of shallow, closely spaced, fine cracks. (Kelly, 1981; ACI 224-84; Perkins, 1986)

B. Thermal Stresses

A drop in temperature may result in cracking in the exposed element, while temperature increase may cause cracking in the protected portion of the structure. These temperature variations result in differential volume changes. Typical visual symptoms of thermal stresses distress is in the form of surface spalls. (Shalon, 1980; Concrete Society, 1982; Berhane, 1992)

C. Alkali-Aggregate Reaction

Generally, this cracking occurs many years after the structure was completed. The crack forms an irregular linked pattern, known as map cracking, and is often confused with drying shrinkage, but the latter occurs in the very early age of concrete. This phenomenon occurs when alkalis released from the hydrating cement react with an aggregate containing reactive silica. The reaction is expansive and results in pop-outs and exudation of a viscous alkali-silicate fluid, which absorbs water and increases in volume. This product may extrude in the form of a colorless viscous gel which carbonates on exposure to air and becomes hard and white. (Concrete Society, 1982; Perkins 1986; Lauer, 1990)

D. Corrosion of Reinforcement

Corrosion is attributable either to the ingress of carbonates to a poor quality porous concrete, or to the percolation or even presence of free chloride ions to the concrete.

Normally, the first indication of damage attributable to carbonation is cracking parallel to the expected direction of the reinforcement. It may be accompanied by rust stains and spalling of concrete cover. The rate at which carbonation develops is dependent on the moisture content of the structure and the relative humidity in the vicinity of the concrete structure. Carbonation neutralizes the protection of steel against corrosion provided by the alkaline conditions of hydrated cement paste. The reaction progressively lowers the saturation level of the alkaline solution which initially has a pH value between 12 and 13. A significant side effect of carbonation is the attendant shrinkage that occurs. When concrete is subjected to wetting and drying cycles in the air, shrinkage due to carbonation becomes worse and irreversible, and this ultimately leads to surface crazing and cracking of exposed concrete. (Parrott, 1990; Mailvaganam, 1992)

Under marine conditions and in other structures where chloride ions are deposited on the surface of concrete in substantial amounts, rapid deterioration of poor quality reinforced concrete occurs. Although most of the chloride present in concrete may have reacted to form insoluble compounds with certain products of cement hydration, a small amount of it remains in solution. The chloride ions tend to destroy the passivating film on the steel even in uncarbonated concrete. (Rasheeduzzafar et al., 1984)

Carbonation is known to destroy the ability of hydrated cement to fix the chloride content. Consequently, the advent of carbonation in the vicinity of steel increases the danger of corrosion even at low chloride contents. Sulphate attack as well leads to the liberation of chlorides into solution and thus aggravates corrosion. Hence, the importance of cover to reinforcement and w/c ratio is emphasized. Other causes of longitudinal cracking, such as high bond stresses, transverse tension, shrinkage, and settlement, can initiate corrosion. (Mailvaganam, 1992)

Corrosion products formed during the process exert a tensile stress on the concrete cover. These stresses increase until they become high enough to crack the concrete cover. The effects of corrosion are usually, splitting cracks along the line of reinforcement, rust staining, and spalling of the concrete away from the rebar leaving it exposed to the environment. (ACI 224-84)

The prevailing highly salt-polluted environment in the Gulf States, puts the chloride ion as the most important cause of corrosion in the area.

Concrete construction on the coastal flats of the Arabian Gulf is continually exposed to ground and atmosphere charged with sulphate and chloride salts. This degree of severe exposure conditions would undoubtedly encourage a rapid deterioration of concrete structures. (Al-Tayyib et al., 1989)

E. Sulphate Attack

When solutions of sulphates penetrate the concrete, sulphate attack takes place. These solutions originate from ground water, soil, or industrial effluents. Sulphate attack is accompanied by expansion and frequently cracking of no distinctive pattern. Where the concrete has heaved or bulged, the cracks often radiate from the center. In other cases, the pattern is random. Concrete severely attacked often has a whitened appearance especially when dry. Occasionally, the attack leaves the concrete soft and mushy while damp. (Lauer, 1990)

Concrete floor slabs made with ordinary Portland cement are frequently damaged by sulphates from the ground. In such a case, sulphates are carried upward in capillary water action, resulting in slab heaving. Construction on reclaimed sites in coastal flats lying within the capillary zone, or sites made with desert fill having suction characteristics are particularly prone to sulphate attack. Sometimes, the attack may damage the mortars and renderings along external surfaces, even up to several feet above ground level. (Rasheeduzzafar et al., 1984)

F. Tensile Cracks

No precise rules can be laid down on how structural defects manifest, and usually considerable experience is needed. In general, diagonal cracks in beams usually denote shear stresses which should not be devaluated. Deflection of beams and other horizontal members suggest overstressing that should be investigated. Deflection is usually accompanied by cracking at right angles to the main bars. Yet, with bowing or overload of vertical members, the cracks may be parallel to the main bars. As well, transverse cracks at regular spacing in the surface of a suspended floor slab may indicate differential movement between the members. (Perkins, 1986)

G. Shear Cracks

Inclined cracking in the webs of reinforced concrete beams may develop either in the absence of flexural cracks in the vicinity, or as an extension of a previously developed flexural crack. The former is known as shear crack, while the later is referred to flexural-shear crack. Flexural cracking is usually expected under service load. If, they extend vertically into the beam without adjoining shear induced cracks, they are though not to cause a sound distress to the beam. (Wang, Salmon, 1985)

In the case of suspected error in design or construction, all effort should be made to obtain original drawings and specification for the structure. If this information is not available, then there is no substitute to either a loading test or other means to check the existing structure against calculations. The reinforcement and the concrete strength should be checked, which requires very detailed assessment. (ACI 224-84)

3.4 Evaluation Techniques

Before attempting to evaluate concrete structures, available techniques and tests usually implemented to achieve this goal should be discussed. Familiarization with testing is a prerequisite to build or use a diagnostic expert system. In order to adopt a certain method of concrete testing, we should choose the suitable testing technique that gives the optimum required information. (Bungey, 1982)

Yet, obtaining an accurate quantitative estimate of in-situ concrete properties may appear to be difficult and troublesome. Several testing techniques exist for the purpose of in-situ assessment of concrete structures. It is evident that for each particular case several different testing techniques may help to collect the required data or results.

(Mays, 1992) had summarized and illustrated the most common techniques Table 3.4. The testing engineer should make a list of all testing required for the cores collected from the site. A brief list may include:

- Petrographic analysis including aggregate-cement paste reactivity.

Table 3.4 In-Service Concrete Inspection Techniques

Test method	*Principal reference*	*Application*	*Property assessed*	*Remarks*
		Structural integrity and layout		
Visual survey including a) crack mapping b) endoscope survey c) photography d) stereo pairs	Bridge Inspection Panel (1984) ACI (1968) Manning & Bye (1983) Cement & Concrete Association (1988)	All elements and structures	Condition and monitoring	Simplest but most important inspection method
Hammer testing Chain drags, etc.	Moore et al. (1973) Savage (1985) Manning & Bye (1983) Cantor (1984)	All elements and structures	Presence of cracks, spalls and delamination	Detects only surface lamination comparative
Covermeter surveys to locate reinforcement, ties	BSI (1986a) BSI (1988b)	All elements and structures	Location and size of steel, and concrete cover	Must be near surface and not congested bars.
Acoustic emission	Mkalar et al. (1984) Hendry & Royles (1985) Manning (1985), BSI (1986a)	All structures during load testing	Initiation and origin of cracks	Specialist inspection equipment and interpretation. Can not detect past stress history
Load testing of structures	BSI (1986c) Menzies (1978), ACI (1985a)	Structures and elements	Deflection under loads against structural analysis	Expensive but informative
		Determination of concrete quality and composition		
Core & lump samples	Concrete Society (1987) BSI (1981), ASTM (1987a)	All elements and structures	Used for physical, chemical and petrographic analysis	Restricted by accessibility. Can be expensive
Power drilled samples	Building Research Est. (1977)	All elements and structures	Chloride, sulphate & moisture content	Simple but subject to errors of depth/cross contamination and sampling
Partially non-destructive assessment of strength, i.e. Windsor probe, internal fracture, pull-out testing, Schmidt Hammer	BSI (in preparation) BSI (1981) Keiller (1982)	All elements and structures	Strength, usually converted to equivalent compressive	Wide margin of error, needs calibration. Detect only surface concrete
Ultrasonic pulse velocity testing	BSI (1985c) ASTM (1987c)	All elements and structures	Concrete quality uniformity, presence of cracks, voids, weak layers, etc.	Rapid but comparative
In-situ permeability tests, e.g. ISAT, Clam	Concrete Society (1988) Montgomery & Adams (1985) Lawrence (1981)	All elements and structures	Concrete quality and permeability generally restricted to cover	slow and difficult. Not true intrinsic permeability. Affected by surface condition.
		Steel serviceability and condition		
Half-cell potential mapping	ASTM (1987f), Baker (1986) Figg & Marsden (1985)	All elements and structures	Likelihood and rate of corrosion of reinforcement	Requires calibration
Resistivity of cover	Manning (1985), Vassie (1980) Wenner (1915)	All elements and structures	Electrical resistance of concrete cover	Four-probe method used with surface electrodes

- Compressive strength, density, absorption, and permeability.
- Chloride content determination.
- Condition of rebar.
- Ultrasonic pulse velocity determination.
- Determination of cement and aggregate contents.
- Chemical analysis of cement paste.

Although a detailed laboratory testing program is unavoidable, the benefits gained through *nondestructive testing* should not be underestimated.

3.4.1 Nondestructive Testing (NDT)

A number of tests for assessing the strength of in situ concrete without taking and testing cores have been developed. The intelligent use of any instrument requires an understanding of what is being measured and limitations of the results. (Perkins, 1986; Mays, 1992) Valuable information about a concrete structure can be obtained from *NDT* and careful observation. Estimating the strength of a concrete component is only one of the functions of *NDT*. The other major areas of *NDT* involve determining the extent of cracking and discontinuities, areas of poor consolidation, presence of voids and honeycombs, locations and size of reinforcing steel, level of moisture, and extent of deterioration that may have occurred due to service, or damage from unusual loading or external detrimental conditions. (Bungey, 1982 ;Mailvaganam, 1992) Test selection is based on a combination of factors such as non-destructiveness, cost, speed,reliability, and limitations of using a specific test.

A. Visual Inspection

A thorough visual inspection is the simplest form of nondestructive evaluation technique, and its importance should not be underestimated. The human eye has an excellent visual perception. The minimum size of a defect that can be detected depends on the surface being examined, the brightness level, and the contrast between the defective area and the immediate background (Mailvaganam, 1992). Surface imperfections such as cracks, excessive deflection, signs of leakage, evidence of movement, and peeling of finishes should be carefully observed and recorded. These may indicate possible deficiencies of structural significance. A partial guide for visual inspection, based on the recommendations of the National Institute of Building Sciences, Washington DC. is included in Appendix A.3.

B. Surface Hardness Tests

The most popular test device to study the surface hardness of concrete is known as Schmidt or Impact Hammer. It measures the hardness by the rebound principle. Although the Impact Hammer provides a quick, inexpensive means of checking concrete quality, it has several limitations. A wide disagreement has been reported concerning the accuracy of the results. It should therefore, be clear that it is not a substitute for standard compressive strength tests on concrete specimens. Yet, the method is quite useful for determining the uniformity of concrete quality in a structure and comparing two areas with similar types of concrete. (Mailvaganam, 1992)

C. Ultrasonic Pulse Velocity Measurements

It is mainly used to study deterioration, cracking, location of unusually large voids in a hardened concrete mass, and to determine the general condition of concrete structures (Bungey, 1982). It is particularly useful to detect the existence and extent of internal cracks and depth of visible surface cracks. Yet, the technique is not recommended for determining the in-place strength of concrete.

D. Half-Cell Potential Test

Measuring the electrical half cell potential of the steel in concrete gives a sensible estimate of reinforcing steel corrosion activity. The results obtained are evaluated to indicate the areas of active corrosion. The test measurements are taken on a grid system on the surface of concrete, and reflect the variation of electrical potential along the member.

E. Concrete Cover to Reinforcing Steel

It is well established that inadequate cover to reinforcement is one of the primary causes of corrosion and subsequent deterioration of the concrete. Therefore, measurement of cover during a condition survey is essential to establish the adequacy of steel protection. A covermeter or a pachometer are used for such task. They can also be used to identify the locations of embedded rebars. (Neville, 1986)

3.4.2 Laboratory Testing

Obtaining suitable samples from a concrete structure is an important part of concrete evaluation. Various laboratory test techniques exist to give a complete assessment of the performance of concrete subjected to any detrimental effect; which will help the efforts put to diagnose the cause of deterioration.

A. Petrographic Analysis

Petrography, defines the procedures and methods of examining and determining properties of rocks and minerals used as concrete aggregates (Dolar, 1983). An example of a data sheet for concrete evaluation is provided in Appendix A.4. Petrographic examination and chemical analysis are powerful methods to provide a diagnostic evaluation of concrete cracking and facilitate determining of the specific cause, e.g., chloride or sulfate attack.

Sampling for petrographic analysis should be done with complete objectivity, so that the sample suitability is not weighted with either the unusually poor or unusually sound materials. The use of modern petrographic techniques furnishes a solid method and powerful tool to determine various characteristics of the concrete, such as: (ACI 207-79)

- Was the correct coarse and fine aggregate used?
- Was the grading of the aggregate satisfactory?
- Was supplementary cementing material used?
- Was the specified w/c ratio used?
- What is the condition of the aggregates?
- What internal reactions has occurred?
- Has excessive carbonation occurred?
- Is the bond with steel not attacked by corrosion?
- Are there any fractures, and what is the distribution?

Examination of polished sections of cores or thin sections, under a low power, stereo binocular microscope, yields information on: approximate composition of coarse and fine aggregate, size and shape of particles, occurrence of cracks, and/or reaction products in concrete. In case alkali-aggregate reaction is suspected, then it is important to determine the chemical constituents of the aggregate particles. Moreover, modern image analysis systems provide means to quantify many features, e.g., air voids, paste content of the mix, and extent of cracking (Mailvaganam, 1992).

B. Compressive Strength of Cores

Many of the desirable characteristics of concrete are qualitatively related to its strength. Therefore, obtaining an exact value of concrete strength is inevitable. (Neville, 1986) specified two primer objectives of testing concrete strength; namely, control of quality and compliance with specifications. Satisfying these objectives would undoubtedly play an important role in the assessment process.

C. Chemical Analysis

Chemical analysis of concrete and mortar are sometimes required to determine the cause of deterioration. Such analysis of specimens is to assure the presence or lack of certain compounds. Procedures like X-ray diffraction, scanning electron microscopy, thermal gravimetric analysis, mercury porosimetry, and differential thermal analysis are usually used in the diagnosis process.

D. Chloride Content

Determination of the chloride ion concentration in the concrete is often required. A number of methods have been developed in recent years, which range from a quick field test on small powdered samples to an analysis of suitable size specimens drilled from the structure. Both water soluble and total chloride ion content can be determined.

E. Sulphate Content

The sulphate content is determined during an investigation to judge the vulnerability of a member to sulphate attack. The sulphate content is compared to the cement content to indicate the attack. Moreover, the test can help to differentiate between agents affecting the concrete according to the existing condition of sulphate salts in the member, as some salts can only be stable in specific levels of alkalinity and change form otherwise.

3.5 Assessment and Interpretation of Results

The interpretation of the results of concrete investigation is dependent on the experience and expertise of the people performing the work. Frequently, advice is needed from specialists in particular fields before conclusions are drawn on the condition and future performance of a concrete structure. The investigator should be familiar with as much information as possible on the reasons why analysis is required and what it is expected to reveal. This understanding should be clear right from the beginning, when all decisions on sample numbers, locations, sizes, etc. have already been decided upon and implemented.

It is always important to bear in mind the objectives of the survey, both to avoid unnecessary work and also to make sure that all the objectives of the inspection program can be met. Frequently it is advisable to perform the work in stages with the assessment of findings at the end of each stage. The extent and detail of a survey should always be governed by the requirement of these information. For example, there is no point in undertaking cement content testing on a structure if there is no reason to doubt the quality of the concrete. (Mays, 1992)

Concrete is a large composite material that can exhibit a wide range of properties and consequently can exhibit a varying range of symptoms of distress caused by structural and material inadequacy, early age cracking, poor workmanship, and bad design and detailing. Therefore, when undertaking an inspection, the first thing that should be considered is how the structure was actually built, what governed, the design and selection of materials and how the steel/concrete was placed on site. Are there any symptoms of inadequate design or poor workmanship and is the overall appearance of the structure consistent with sound design and construction practice?.

The second aspect which should be considered is the loading imposed on the structure and the degree of maintenance/repair work previously undertaken. Have any joints, for example been replaced? Has any drainage system present been maintained? Are there any signs of excessive loading/deflection/creep and has any cracking been induced? What are the provisions for accommodating thermal movement and differential settlement and are these satisfactory?

Environment comes next, which should be examined in detail, particularly during periods of wet weather or draught. Are expansion joints functioning and waterproof? Which areas are permanently wet and which areas alternatively wet to dry?

Finally, when the results of the site and laboratory work are complete and conclusions are being drawn, it should be remembered that all the test techniques are complementary and none, on its own, is definitive. A combination of test and inspection techniques is invariably adopted to form a sound realistic assessment for the condition of the structure. Provided the work has been done correctly, there should be no discrepancy in the results and the various test methods should act together to build up a picture of the construction, condition and current state of the structure.

CHAPTER 4

METHODOLOGY

This chapter establishes the procedure that is followed for the development of the diagnostic domain expert system. The system is named ***CONCEXS*** (*CONC*RETE *EX*PERT *S*YSTEM). Basic development phases are identified in terms of their procedures and aim beyond following them. Moreover, examples are given to represent the type of required data and how to acquire this knowledge. General evolution steps are established in this chapter to be implemented and fully detailed in Chapter 5. The chapter explains the generalized decision path of the system and depicts how to group and correlate the acquired knowledge to achieve the diagnosis task. Finally, a discussion is included about ***GURU***, the adopted building shell for developing CONCEXS.

4.1 The Development Cycle

The development process of ***CONCEXS*** can not be easily defined by a recipe of simple steps to be followed. The inherent complexity of the process prohibits laying out all of the steps in advance. Instead, an evolutionary process of development is most useful for developing expert system applications. The expert system development process consists of five interdependent and overlapping phases: (Guru, 1989; Yeh, et al., 1992; Waterman, 1986)

- Identification.
- Conceptualization.
- Formalization.
- Implementation.
- Testing and maintenance.

Fig. 4.1 illustrates the stages in the evolutionary development cycle. In most cases, testing the knowledge system indicates shortcomings in the earlier stages of construction. As the system development progresses and rules are developed for each component, new rules are found to fulfill initial goals. These changes and additions impact earlier stages of the development cycle, fulfilling the evolutionary process of system development. In contrast to conventional programming, rule-based programming requires more analytical thinking than procedurally oriented thinking. Instead of systematically outlining goals and then implementing a corresponding sequential problem solving program, the general approach of a rule-based problem solving should be carefully understood.

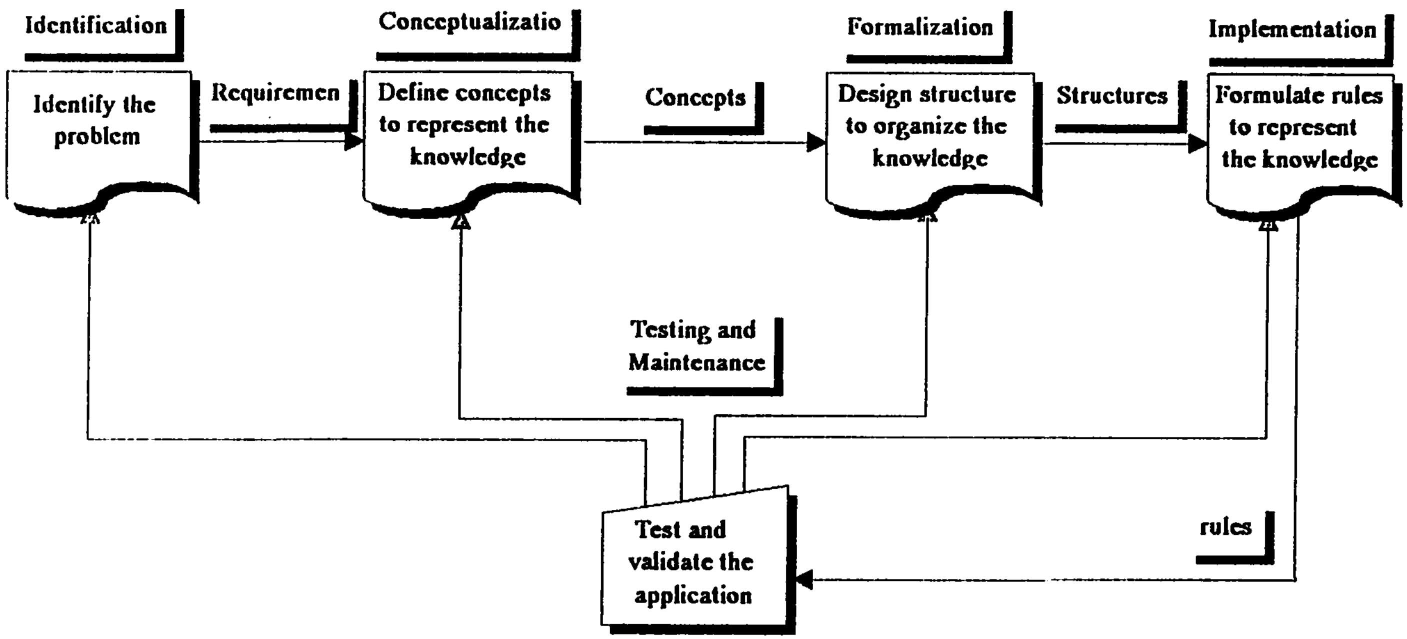


Fig 4.1 Stages in the Expert System Development Cycle
(after Waterman, 1986)

4.1.1 Identification

During the *identification* process, the aim is to define the objective and identify important features of the application. At this stage, all components related to the problem must be identified, to define the domain of application (e.g., type and scope), the important features of the problem, the required resources (e.g., computing facilities), and the goals or objectives of building the expert system.

Clearly enough, this task has already been carefully achieved in the previous chapters, where the problem was carefully stated and defined to automate the process of diagnosing residential concrete structures. More specifically, three members were selected; namely: slabs, beams, and columns to be covered within the domain of the diagnosis task. The reason beyond this limitation is to scale down the complex and vast amount of knowledge needed to a manageable size.

Moreover, the suitability of the problem for expert system development was investigated, keeping in mind the problem complexity and what previous related work has been done. A summary of the problem description is depicted in Table 4.1

4.1.2 Conceptualization

The requirement to fulfill this task is to decide what concepts, relations, and control mechanisms are needed to describe and satisfy the

Table 4.1 Initial problem description for *CONCEXS*

Category	Description
Goal	Assist field inspectors and maintenance consultants to diagnose concrete defects
Main Problem	Diagnose cause of concrete defects in structure slabs, columns and beams
Sub Problem	Define structural system. Define members condition. Identify the defect. Follow diagnosis techniques.
Important Concepts	See chapter 3
Problem Characteristics	Huge knowledge. Vast array of controlling factors. Complicated relations.
Data	Literature data. Case studies. Field trips.
Solution	Causes of deterioration .

diagnosis problem in the domain of residential concrete structures. Moreover, subtasks, strategies, and constraints related to a structure and hence would affect the problem-solving activity need to be explored. This exactly defines at what level of detail the knowledge should be represented.

In conceptualization, facts about elements and relationships pertaining to each member are expressed in sentences that would facilitate a diagnostic aim. An element defines any attributable characteristic that plays a role in the behavior of a member. A relation, on the other hand, is a characteristic or trait of a group of elements with respect to each other (Yeh, et al., 1992).

In order to identify and conceptualize the domain of the intended expert system, a thorough study of the literature as well as the practice in the field is conducted. This is aimed to get sufficient familiarity with the problem domain; namely, deterioration of concrete slabs, columns and beams. The primary task of the expert system is decided to be identifying the anatomy of structural concrete buildings and their detailed condition in order to diagnose the case of deterioration and the cause that resulted in that degradation in performance if any.

4.1.2.1 Data Required

The data required to conceptualize the expert system is framed thoroughly to cover the following data pertaining to concrete slabs, columns and beams;

- Member definition
- Defect identification
    - Type
    - Behavior
    - Location in member
    - Direction
    - Other symptoms
- Required tests for assessment purposes
    - Array of variable test procedures frequently adopted
- Recommendations for diagnosis process
    - Design load
    - Soil condition
    - Soil bearing capacity
    - Environment condition
    - Material constituents (aggregates, cement, water, . . .)
    - Reinforcement
    - Chemical analysis
    - Concrete quality (permeability, strength, . . .)
    - Service conditions
    - Others
- Diagnostic decisions

A sample for the proposed structure of the system.

Level 1 (Symptoms string)

Array of choices describing most expected symptoms, arranged according to structural systems.

The user may select one or more of these symptoms.

Level 2

A list depicting required information to be ascertained, is developed and displayed to the user, guiding him to perform required tests and confirm the possible effect of controllers (suspects).

Example for Level 2

Check for settlement of foundation through:

REQUIRED INVESTIGATION	RESPONSE
Design check?	*OK.*
Is there structural additions?	*NO.*
Is there structural alterations?	*NO.*
Check design safety (Bearing capacity)?	*OK.*
Is building being used according to its design?	*YES.*
Check subsoil plus weather condition?	*SUSPECTED.*

Level 3

A list is generated to accept inputs of the user's investigation, which is processed to come up with the required answers.

(Additional questions may be developed to come up with a more defined cause, subject to return back to level 2).

The result is collapsible subsoil and a prolonged duration of draught had prevailed.

4.1.2.2 Knowledge Acquisition

The knowledge required to develop the intended system was gathered by adopting the following methodology:

1. Search in the literature for general structural and concrete defects mostly encountered, how to assess them, then defining appropriate courses of action frequently implemented to investigate these defects.
2. Tracing concrete defects mostly encountered in the Kingdom by meeting concerned authorities and maintenance consultants.
3. Interviewing maintenance and consulting experts to understand how they identify symptoms of building defects, and how they commence concrete diagnosis procedures.

4.1.3 Formalization

Formalization involves expressing the key concepts and relations outlined during conceptualization. This process is going to be achieved through the use of a graphical representation approach with dependency diagrams or *Decision Trees*. A decision tree is a visual representation of the factors pertinent to the problem area and the relationships of those factors (Frenzel, 1987). The dependency diagram is an essential tool for representing information and facilitating the rule creation process.

Before we go any further, some important terminology need to be reviewed and introduced as follows:

Variables: are the attributes or factors that influence the classification or decisions. They define the parameters upon which the system builds up its logic and proceed with the diagnosis task (e.g., soil type, chlorides content, crack location, . . .).

Values: Each attribute has several possible values that show a group of facts or array of several situations. Each single value defines a single fact, a condition, or a situation a variable can take (e.g., for *variable soil*, possible values can be collapsible, expansive, well confined soil).

Decision: is a prediction or diagnosis of a group of conjoined variable-value pairs. For instance, in diagnosing a concrete defect, such as slab settlement, possible decision value can be design deficiency, misestimation of bearing capacity, and/or ignorance of existing poor soil bedding.

Decision tree: is a tree type structure encoding a set of tests on attributes to classify objects into fixed categories (decision values).

In order to visualize the elements of knowledge in a knowledge base, a flow chart can be drawn using nodes and arcs. Each node represents one fact, rule, or another knowledge element. The nodes are interconnected with arcs showing the relationships. The initial state of search process is referred to as the root node. Growing downward from the root node, the branches extend to successor nodes. Each additional node has one or more successors. The tree keeps on growing and expanding until a decision is eventually reached. (Frenzel, 1987)

In most expert systems, the search space is far too large to draw the decision tree for the knowledge base. For that reason, in the intended expert system, decision trees are segmented to depict a specific single root, i.e., corrosion in grade slabs. This concept helps explain how an inference engine searches through a knowledge base.

4.1.3.1 Decision Trees Construction Procedure

In order to proceed with the development of decision trees for different defects, first a kind of data sheets is formed for each defect pertaining to a specific structural member. These data sheets depict the collected information and facts about each defect case. The format thereunder is used.

Member	*Structural member*
Defect	*deterioration type*
Symptoms	*deterioration manifestation*
Checks	*facts to be ascertained for diagnosis*
Decisions	*array of causes of the defect*

The data collected in these defect cases is then correlated and organized in the form of decision trees. The basic procedure adopted for constructing a decision tree (CDT) is as follows (Yeh, et al., 1992):

1. Splitting of root. For the root node, an attribute is selected and a set of new subtrees is created according to the possible values of that attribute. Each new subtree comprises all the examples with a certain value of the selected attribute.
2. Checking of subtrees. Each new subtree is checked whether it leads to a decision value or it still needs further expansion to reach a decision value.
3. Termination criteria. If all new subtrees directly lead to a goal decision, then go to step 5; otherwise go to step 4.
4. Splitting of subtrees. For each non ending subtree, untested attributes are selected and a set of new subtrees is created as step 1.
5. Return decision tree. The decision tree is generated and satisfactory; return and exit.

The previous procedure gives only an outline of the evolution of decision trees. but it is not necessarily followed strictly. This is true as the procedure should be flexible enough to allow for short cuts and reorganization of the nodes until a logical flow of infrencing is achieved.

The following chapter will depict the detailed decision trees pertaining to different defect cases. Fig 4.2 shows a generalized decision tree of the diagnosis problem, where the path of inference through associated attributes is depicted.

4.1.4 Implementation

The process of associating rules with the relationships and converting all formalized knowledge into production rule format is referred to as implementation (Waterman, 1986). In this phase, a decision tree is converted to a set of rules. To reach a certain leaf, an object must satisfy all the conditions (variable-value pairs) specified in a particular path from the root to the leaf. Each decision tree path corresponds to a rule in the form:

If	A = A_i	&	B = B_j	&	C = C_k
Then	Dec = Dec_n				

where A, B, and C indicate variables; A_i, B_j, C_k indicate their assigned values, respectively. Dec indicates a decision whether it is a subgoal or a goal; and Dec_n indicates the value of Dec.

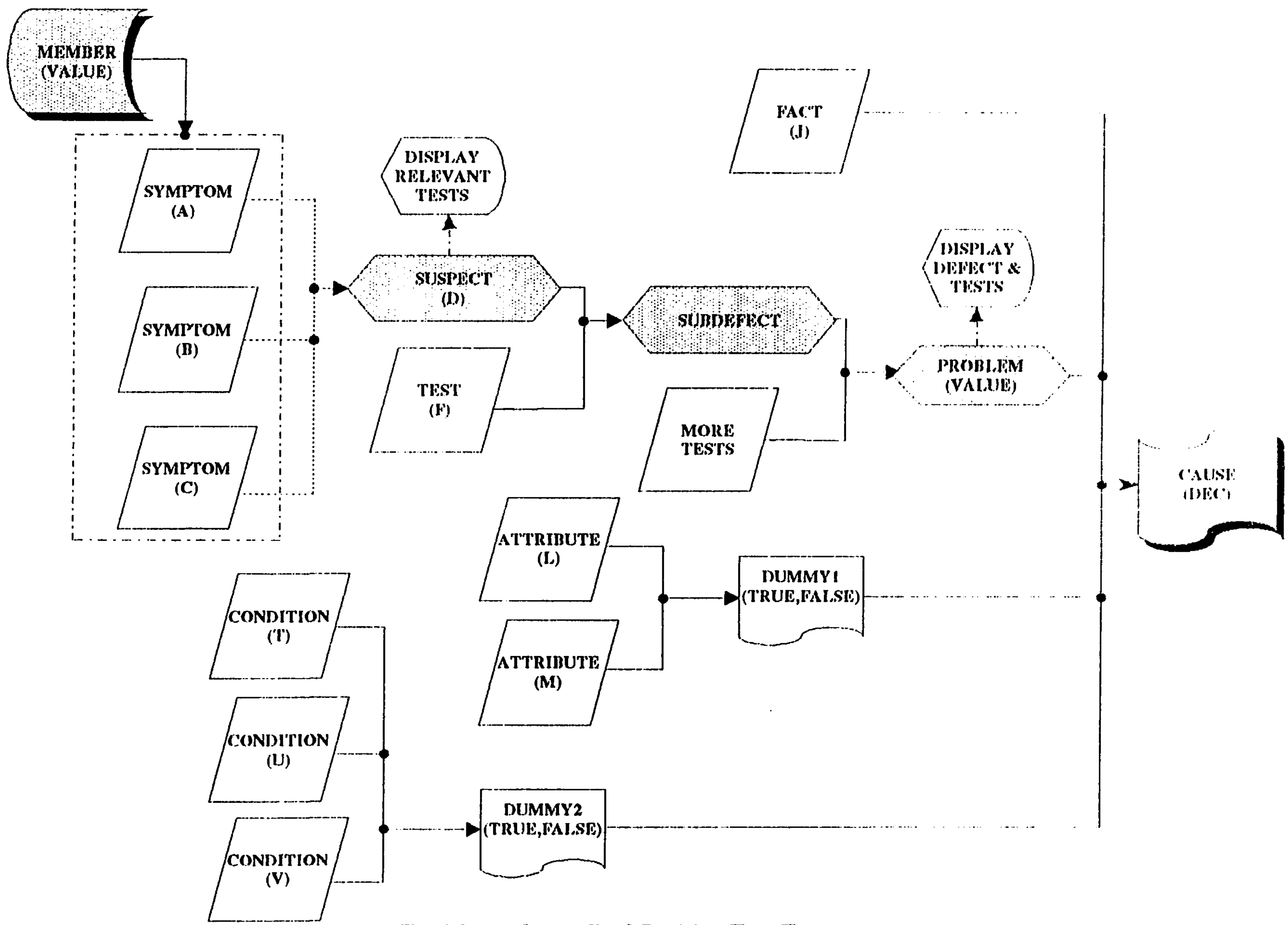


Fig 4.2 A Generalized Decision Tree Format

4.1.4.1 Structure of the System

The proposed system is to be structured to facilitate a kind of easy friendly interaction between the user and the system. This structure is to be achieved through categorizing the consultation environment in three main categories, (as dipected in Fig 4.3):

1. ***User Input:*** the system guides the user into a certain direction to input knowledge into the system defining the structural system, defect symptoms and related aspects. The result is a proper identification of the defect.
2. ***User-Expert Interaction:*** the expert system provides a list of required information to facilitate the diagnosis task. Upon feeding these information, the system goes on manipulation and infrencing the input data to perform a satisfactory diagnosis procedure.
3. ***Expert Output:*** to develop suitable decisions concerning the agent beyond the defect condition and the cause that resulted in it.

During a diagnosis session, *CONCEXS* is to be designed to start by collecting background information and defect symptoms. Powered with the inference mechanism, the system starts on triggering its diagnostic procedures. The system uses the input information in addition to its own knowledge in the form of production rules to perform its deduction and diagnosis. This process activates new procedures associated with progressively inferred facts, and rules, which control and reorganize the reasoning process. If additional required information is required, the

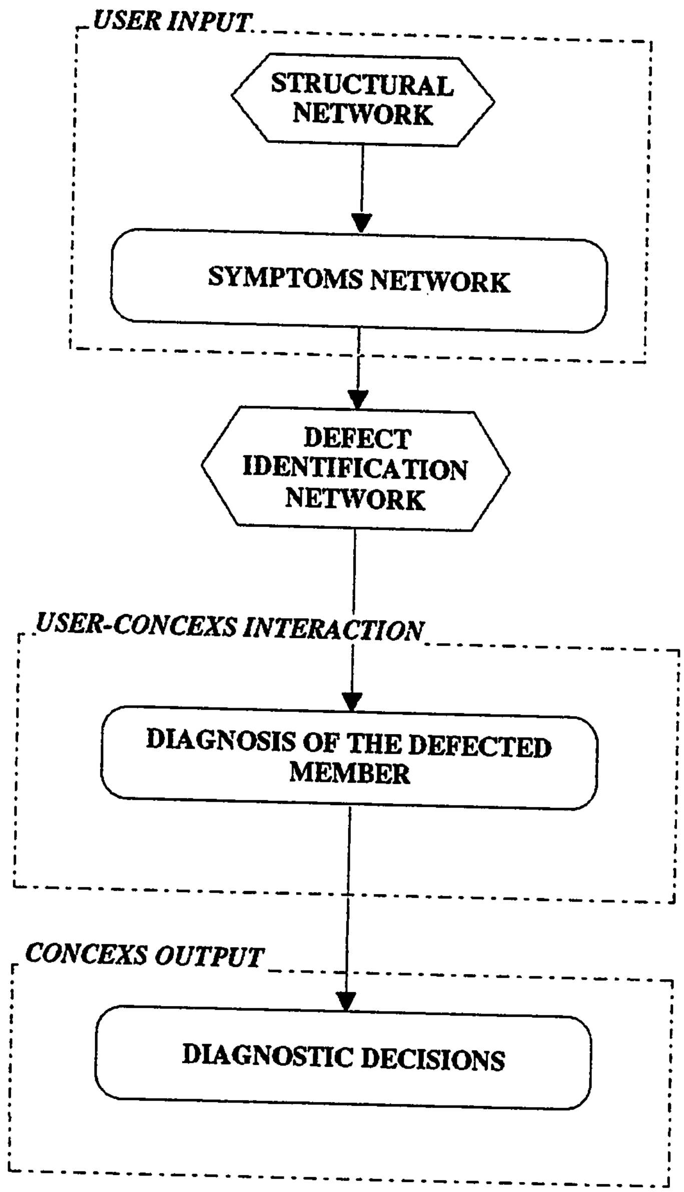


Fig 4.3 Decision Path During a Diagnostic Consultaion Session

system requests the information from the user by displaying forms to feed the input data. Finally, after the system satisfies its diagnostic procedures, it generates the result of its thorough search among its reasoning strategies. The output is thought to be a list of the type of defect along with its associated cause of deterioration. This procedure is displayed in Fig 4.4, but it is going to be further detailed in the next chapter.

4.2 Expert System Shell

Choosing the right development tool for building the expert system passed through a careful selective process. This challenge was realized due to the fact that many of the earlier research tools evolved from specific expert systems by stripping systems of their domain knowledge. Some of the recent commercial tools incorporate what AI researchers consider to be the most promising new ways of representing knowledge, hoping that these will make the appropriate tools for more types of problems. The difficulty arises mainly due to the dilemma of what tool features suit specific classes of problems. In order to select a suitable building tool to accommodate the features and enhance the performance expected by the intended expert system, several tools were checked and later on rejected either due to their limitations or non suitability to the proposed application. On this route two expert systems shells were adopted; first EXSYS, then CLIPS. None of these tow shells were satisfactory, either due to expandability limitation, or complexity of use. Eventually, another

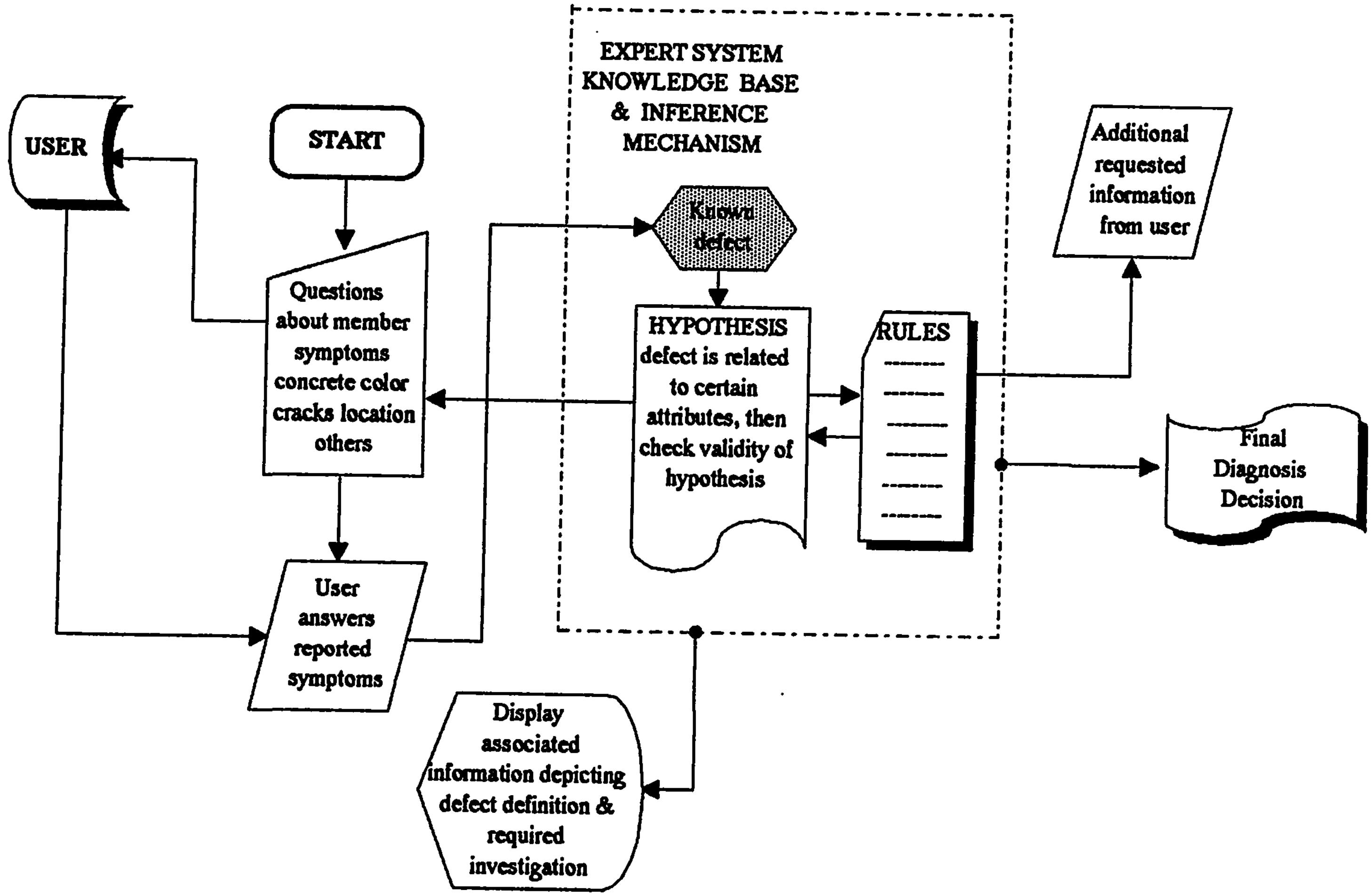


Fig 4.4 Diagnosis Expert System Architecture

shell was evaluated and found to be suitable for building the diagnostic knowledge-base system. The shell adopted to build the proposed system is *GURU*.

4.2.1 Shell Requirements

GURU was selected to meet several challenges; namely,

1. It offers more guidelines and mechanisms for how to represent and access the systems knowledge.
2. It makes the development process easy, faster and even more cheaper than with a programming language.
3. Support Facilities: GURU includes support facilities that speed up development and thus save time and enhance the performance of the built expert system.
4. Reliability: GURU is a well established commercial building tool that has been extensively used to develop several versatile expert systems.
5. Task Characteristics: The features of the problem of concrete diagnosis involves certain type of characteristics that derive specific symptoms and require a unique kind of solution. These features suggest particular tool features needed by the expert system itself. The intended application is characterized by its handling of diverse types of knowledge, complicated analysis of symptoms, input-output interaction and performance of diagnosis and proposal of a suitable solution. These facts require a kind of question-answer input which

is translated in expert system language as a representation called rule based format (Waterman, 1986).

This character of the intended application recommends *GURU* to be adopted as a suitable building tool. For reference purpose *GURU's* major design specifications are included in Appendix-C.

4.2.2 Why Using a Rule Based System

At this stage it is useful to know that a rule based system was adopted as a mean for representing knowledge gathered for this study. Several factors favored its use rather than any other representation method. Besides familiarness and popular use of this method in the diagnosis domain, other factors may be, but not limited to, the following (Kalyanasundaram, et al., 1990):

1. Production rules are simple and very readable. Debugging and validation of the system would be easily performed and achieved for any domain expert who may wish merely to browse through the rules in order to check the system.
2. Any expert system is being built with its expandability is a must that should be kept in mind while being built. So, using a rule based method of representation facilitates any needed updates, addition or correction to the system.

3. Availability and flexibility of expert system development with knowledge representation in the form of production rules.

The following chapter will detail how the features of concrete diagnosis problem were formatted by using GURU developing procedures.

CHAPTER 5

A DIAGNOSTIC EXPERT SYSTEM FOR CONCRETE STRUCTURES

As mentioned before, the problem domain of this study is the defect diagnosis of a concrete slab, beam, and/or column. It was found that several factors control the behavior of these members. These factors are: material constituents, construction practice, design and environment. According to these factors, the studied members were found to be subject to specific deteriorating actions; such as, corrosion, sulphate attack, loss of structural integrity, . . . etc.

It is the aim of this chapter to illustrate the specific defect causes found frequently in the environment of Saudi Arabia. The chapter addresses each problem, how it is documented, its related aspects, and how to diagnose the factor most suspected to cause deterioration. Each case is illustrated separately then formulated in a decision tree form to be suitable for encoding as production rules. This procedure is adopted to satisfy the objective of building the diagnostic expert system.

In this chapter all suggested variables are explained along with their interrelating relations and drawn decisions. Furthermore, rules building is mentioned along the development process to establish the reasoning and decision making strategy of the expert system.

5.1 Knowledge Base

The knowledge base as defined previously is the heart of the expert system. It controls all the deciding expertise upon which a decision can be made. *CONCEXS*'s knowledge base is documented in special format that is going to be explained in this section.

5.1.1 Selected Problems

The concrete diagnosis knowledge base acquired for the purpose of this study was carefully collected, selected and documented. The aim was to ease the process of conceptualizing and formalizing the knowledge base. The phase of data collection was achieved through careful study of several documented cases. The cases histories were obtained from local repair consultants and repair materials suppliers. These cases were further traced and compared against the literature to have a better understanding of each and to get acquainted with their related aspects, symptoms, governing factors, and contributing agents. Furthermore, it was intended to reach a well known notation of representing these cases.

The obtained cases, in terms of frequency of occurrence, show that the main categories of concrete deterioration in the local environment are attributable to the following:

1. *corrosion of reinforcement.*
2. *sulphate attack.*
3. *carbonation.*
4. *alkali-aggregate reaction.*
5. *ground slab heaving.*
6. *slab settlement..*

These are the most frequent problems, which represent the domain of this study and the knowledge base for the diagnostic expert system. Moreover, some other problems do occur in the area but not as frequent. So, some of these problems are documented and added to the knowledge base to facilitate any intended future expansion of the system. These problems include:

1. *flexural or tension cracking in beams.*
2. *shear cracking in beams.*
3. *beams bond failure.*
4. *column buckling.*

The collected problems were traced as far as possible to the most affected member. In other words, symptoms attributable to a specific problem were documented according to the member on which these symptoms manifested. This method holds due to the fact that some problems may show different symptoms on different members. Moreover, several problems may share same symptoms which may mislead any diagnosis effort. Keeping all these factors in mind, the problems were subdivided according to each member into several sub-problems, each concentrating on a specific defect case. This analogy suggested the general structure of sub-problems shown in Fig 5.1.

5.1.2 Defect Cases

After settling on the chosen set of defects, each is thoroughly documented in a separate defect case sheet designed for this purpose. While documenting the acquired knowledge pertaining to each problem and sub-problem, discussions with the domain expert directed the documentation process. This careful checking of the knowledge is essential for the sake of producing easily understood decision cases. The output is several defect cases sheets, each geared with related attributes possessing and leading to specific decision values. Each defect case sheet represents an expert's overall information about a specific problem. Fig 5.2 lists a sample defect case that defines the knowledge acquired for a corrosion of slabs case, the rest of the documented defect cases is included in Appendix-D.

A typical defect case starts with defining the defected member, whether it is a beam, a column, a slab or a slab on grade. Then, it declares a specific problem among the ones most frequently encountered.

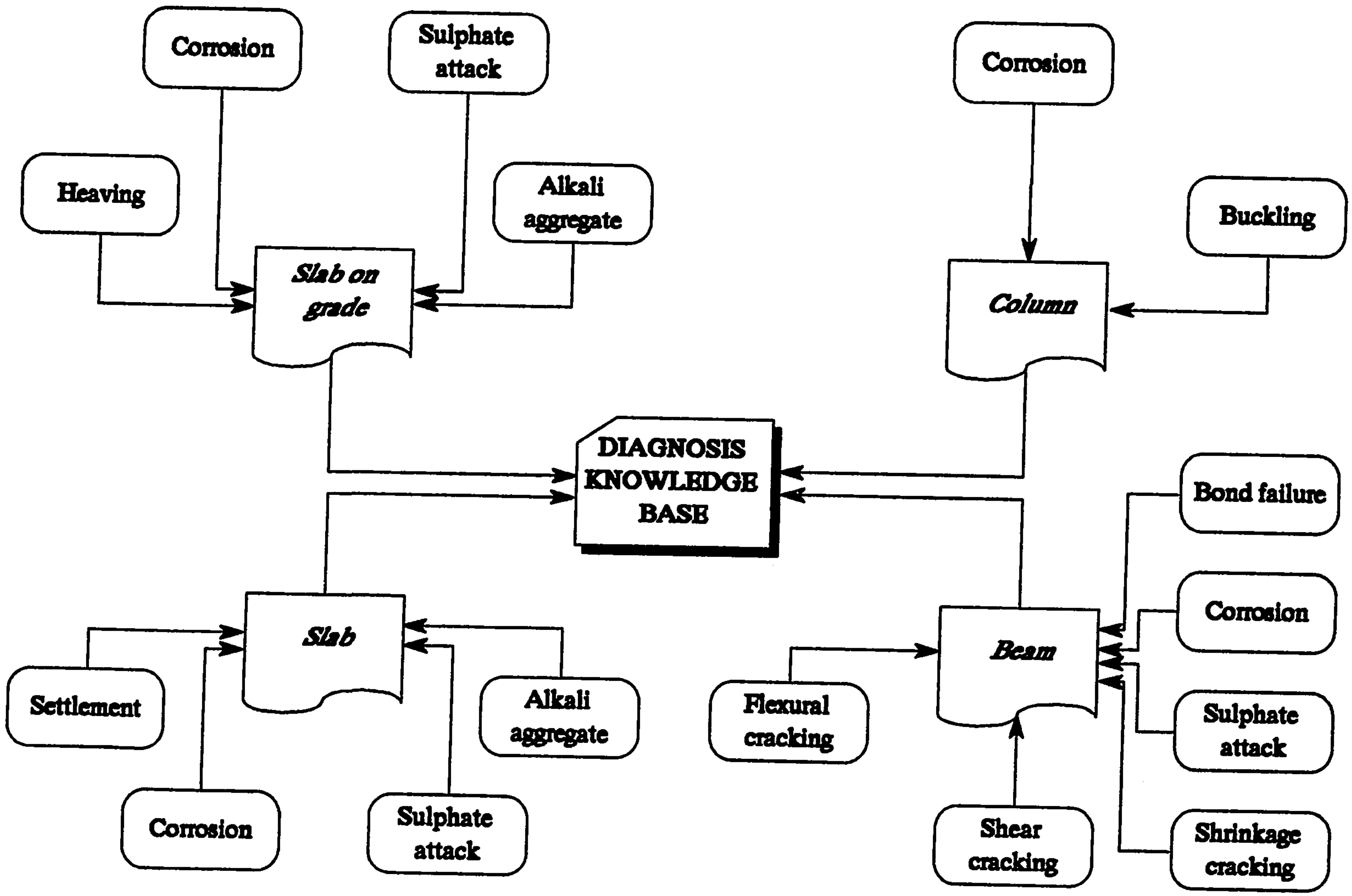


Fig 5.1 Domain of Problems Covered by CONCEXS

CASE S4 :	
MEMBER :	Concrete slab (elevated or ground slab).
PROBLEM :	Corrosion of reinforcement.
SYMPTOMS : • Splitting cracks running along reinforcement. • Spalling of concrete cover. • Rust stains.	
LOCATION :	Along the reinforcement.
CHECKS : 1. Perform cover meter test 2. Expose reinforcement. 3. Perform half-cell potential test. 4. Conduct chloride content and depth tests. 5. Conduct carbonates content and depth tests. 6. Check concrete quality.(permeability, used water). 7. Check aggregates quality. 8. Conduct chemical analysis of subsoil. 9. Conduct chemical analysis of ground water.	

Fig 5.2 Defect case sheet for corrosion on slabs

Afterwards, the symptoms or manifestation of each problem that may guide the process of identifying each problem are listed. Finally, the sheets address expert's opinion concerning the adopted suitable testing methods to reveal the agent causing the deterioration.

Thorough literature review was carried out to compare and capture the most commonly used notation of representing concrete deterioration knowledge. The defect cases were tested with the domain expert to achieve a satisfactory and sufficient degree of clarity of representation.

5.1.3 Variables

The selected concrete defect cases were carefully analyzed to find the most suitable means of formalizing the knowledge base. During this stage a step by step study of every attribute was unavoidable to find ways to identify the attributes' specific characteristics. Understanding these characteristics helps the approach to combine and correlate them. Additionally, relevant decision values are assigned to certain grouped attributes of the concerned problem.

The quality of the simulated logical decision making process through the expert system depends on the selection of attributes. A poor set of attributes may result in a poor decision tree. Selection of the attributes is not a haphazard procedure and demands professional experience. The step by step discussions were very productive during this stage in the sense that they facilitated appropriate selection of important features to be formed into attributes or -in ES terminology- variables. It was possible to define each variable based on its suitability to the decision making process.

The variables were designed to cover all of the attributes that concern the studied problems. For that reason the variables are classified into the following categories: (Table 5.1 illustrates the different categories of variables and the variables that lay in each category.)

1. Symptoms variables: They define the attributes which control the symptoms or manifestation of deterioration in a member.
2. Diagnostic variables: These illustrate the attributes which govern the diagnosis procedures. They define the checks that need to be ascertained to derive a diagnostic decision.
3. Dummy variables: They are non-functional variables from the knowledge base point of view. Yet, they help to split think among various search roots. For example, if a value is reached to testify that corrosion is confirmed, then the system concentrates only on rules related to the corrosion problem, discarding other search roots. This way of analysis is performed by the action of the dummy variable *CORROS.*
4. Decision variables: They declare the obtained decision after a certain search level is performed. They may, furthermore, define either goals or sub-goals. A goal decision variable is the ultimate target of the

Table 5.1 List of Developed Variaables Categories and Their Description.

Category	Variable	Definition
Symptoms	SCRACK	Crack behavior in slab
	SSYM	General slab performance
	STIME	Time of occurrance
	SRELATE	Other affected members if any
	SAPPER	Slab surface appearance
	SCONC	Concrete surface condition in slab
	SLOC	Location of defect in a slab
	CRAKWID	Crack width in a beam
	CRAKLEN	Crack length in a beam
	CRAKDIR	Crack direction in a beam
	BSYM	Beam surface appearance
	BCONC	Concrete surface condition in a beam
	BLOC	Location of defect in a beam
	CRAKBEHV	Crack behavior in a column
	CCRAK	Crack direction in a column
	CSYM	Column surface appearance
	CCONC	Concrete surface condition in a column
	CLOC	Location of defect in a column
Diagnostic	POT	Half cell potential
	CL	Chlorides content
	PH	Concrete Alkalinity
	CO	Depth of carbonation
	SL	Sulphates content
	PERM	Concrete permeability
	QUALITY	Overall concret quality
	AGG	Aggregate quality
	CEMENT	Cement type
	WC	Water cement ratio
	COVER	Concrete cover to reinforcement
	MIX	Concrete mix design
	STRENGTH	Concrete strength
	SOIL	Soil type
	GWATER	Ground water quality
	SOILCONT	Soil chemical analysis
	MOMENT	Bending moment consideration
	BEARCAP	Bearing capacity consideration
	STEEL	Reinforcement provision
	ENV	Environmental conditions
	SHEAR	Shear design considerations
	SERVICE	Structure service conditions
	COL	Column slenderness ratio
Dummy	MEMBER	Defected member
	CORROS	Corrosion confirmation
	INTERNAL	Internal cause of defect
	EXTERNAL	External cause of defect
	SUSPECT	Chemical deterioration type
	ELEMENT	Member type
Decision	PROBLEM	Defect type
	CAUSE	Factor causing the defect

diagnosis process. While, a sub-goal variable is the one that ends a level of search, i.e., problem identification level. Then it triggers certain database that directs the diagnosis process in a certain search route.

These variables contain the decision values which suggest different decisions and direct the search, depending on the value each variable may possess. At this stage and for the purpose of this study a certain degree of generalization is assumed while suggesting the values. For example, variable *SOIL* is said to possess values like {collapsible, expansive, well confined}, but some other values are included only for future expansion. These values were suggested rather than a detailed listing of the type of soil, like {clay, silt, rock, . . . etc.}. The reason is the limitation of both time and space in this study. Besides, in case we go for greater degree of detailing of information, the amount of knowledge base to be handled will be tremendous and needs excessive formalization. For the satisfaction of this study objectives, the obtained information is considered sufficient with the agreed upon degree of generalization.

Moreover, certain values are grouped together into variables based on the relevance and the logic of attaching these pieces of information together rather than splitting them. Although grouping decision values rationally adds to the power of the system, it should be established on the basis of common characteristics between the values. For example, a variable *SCRACK* is used to combine the characteristics of induced cracks in a slab. It holds values like {cracks tend to close and open, map cracking, diffused or non pattern cracking, splitting cracks}. All these values have one thing in common, which is crack description, so whenever the user is asked about the behavior of the induced crack, he is not lost between independent fragments of information. Clearly enough, this will enhance the diagnosis process, accelerate it and furnish a more realistic question-answer dialog with the user.

It is worth mentioning that two specific variables *PROBLEM* and *CAUSE* are designed as array variables so that they may possess more than one value simultaneously. This occurs when there are two or more induced problems, like corrosion and slab settlement. Such design simulates real life co-occurrence of several problems simultaneously, or the action of several different factors that ended up in the loss of integrity or deterioration.

The following list includes the developed variables along with their various values.

VAR:	**MEMBER**
LABEL:	DEFECTED MEMBER
VALUES	SLAB
	SLAB ON GRADE
	BEAM
	COLUMN

VAR:	**SCRACK** **(A)**
LABEL:	CRACK BEHAVIOR IN SLAB
VALUES:	THEY TEND TO CLOSE AND OPEN
	MAP CRACKING, OF IRREGULAR LINKED PATTERN
	DIFFUSED OR NON PATTERN CRACKS DEVIATE FROM CENTER
	SPLITTING CRACKS RUNNING ALONG REINFORCEMENT
	IRREGULAR OR NON PATTERN CRACKS IN ALL DIRECTIONS
	NON OF THE ABOVE

VAR:	**SSYM** **(B)**
LABEL:	GENERAL SLAB PERFORMANCE
VALUES:	SLAB IS IRREGULAR AND PUMPING
	SLAB EDGES ARE NOT LEVELLED
	SLAB SURFACE IS CRACKED AND EXPANDED
	SLAB SURFACE IS HEAVING AND PULGING
	NON OF THE ABOVE

VAR:	**STIME** **(C)**
LABEL:	TIME OF OCCURENCE
VALUES:	PROBLEM OFTEN OCCURS SEASONALLY AFTER A HARD RAIN
	DISTRESS OCCURRED SUDDENLY
	PROBLEM OCCURRED OVER A CONSIDERABLE TIME
	NON OF THE ABOVE

VAR:	**SRELATE** **(D)**
LABEL:	OTHER AFFECTED MEMBERS IF ANY
VALUES:	TOP OF COLUMN IS HUGGING INWARDS
	TOP OF COLUMN IS HUGGING OUTWARDS
	POSSIBLE DOOR OR WIDOW JAMMING
	NON OF THE ABOVE

VAR:	**SAPPER** **(E)**
LABEL:	SLAB SURFACE APPEARANCE
VALUES:	EFFLORESCENCE AND DISCOLORATION OF SLAB
	SLAB IS WHITENED WHEN DRY
	RUST STAINS
	A COLORLESS VISCOUS WHITE GEL THAT SWELLS WATER
	NON OF THE ABOVE

VAR:	**SCONC** **(F)**
LABEL:	CONCRETE SURFACE CONDITION IN SLAB
VALUES:	POPOUTS WITH SPILLS
	EXPANSION AND CRACKING OF AGGREGATE PARTICLES, CEMENT PASTE
	CONCRETE IS SOFT AND MUSHY WHEN DAMP
	SPALLING OF CONCRETE COVER
	CRACKS ARE DEEP THROUGH THE SLAB
	NON OF THE ABOVE

VAR:	**PROBLEM**
LABEL:	DEFECT TYPE
VALUES:	SLAB HEAVING
	SLAB SETTLEMENT
	ALKALI-AGGREGATE REACTION
	SULPHATE ATTACK
	CORROSION OF REINFORCEMENT
	DRYING SHRINKAGE CRACKING
	TENSION OR FLEXURAL CRACKING
	SHEAR CRACKS
	BOND FAILURE
	COLUMN BUCKLING
	NON OF THE ABOVE

VAR:	**POT** **(G)**
LABEL:	HALF CELL POTENTIAL
VALUES:	POTENTIAL < ALLOWABLE
	POTENTIAL > ALLOWABLE

VAR:	**CL** **(H)**
LABEL:	CHLORIDES CONTENT
VALUES:	CHLORIDE CONTENT < ALLOWABLE
	CHLORIDE CONTENT > ALLOWABLE

VAR:	**PH** **(I)**
LABEL:	CONCRETE ALKALINITY
VALUES:	PH VALUE IS WITHIN ALLOWABLE
	PH VALUE IS NOT WITHIN ALLOWABLE

VAR:	**CO** **(J)**
LABEL:	DEPTH OF CARBONATION
VALUES:	CARBONATES DEPTH < ALLOWABLE
	CARBONATES DEPTH > ALLOWABLE

VAR:	**SL** **(K)**
LABEL:	SULPHATES CONTENT
VALUES:	SULPHATES CONTENT < ALLOWABLE
	SULPHATES CONTENT > ALLOWABLE

VAR:	**PERM** **(L)**
LABEL:	CONCRETE PERMEABILITY
VALUES:	CONCRETE IS DENSE AND NON-PERMEABLE
	CONCRETE IS HIGHLY POROUS

VAR:	**QUALITY** **(M)**
LABEL:	OVERALL CONCRETE QUALITY
VALUES:	CURING PRACTICE IS PROPER AND THOROUGH
	CURING PRACTICE IS POOR AND IRREGULAR
	CONCRETE IS POORLY COMPACTED
	POOR OR UNEVEN FORMWORK

VAR: **AGG** **(N)**
LABEL: AGGREGATE QUALITY
VALUES: AGGREGATES CONTAINING SILICA SALTS
HIGHLY POROUS AGGREGATES
AGGREGATES CONTAMINATED WITH CORROSIVE SALTS
AGGREGATES CONTAMINATED WITH SULPHATES
GOOD QUALITY AGGREGATES

VAR: **CEMENT** **(O)**
LABEL: CEMENT TYPE
VALUES: TYPE I CEMENT
TYPE V CEMENT
POOR QUALITY CEMENT
OTHER

VAR: **WC** **(P)**
LABEL: WATER CEMENT RATIO
VALUES: W/C CONTENT IS LOW
W/C CONTENT IS HIGH
W/C CONTENT IS ADEQUATE
ADDITIONAL WATER WAS ADDED DURING CONCRETING

VAR: **COVER** **(Q)**
LABEL: CONCRETE COVER TO REINFORCEMENT
VALUES: CONCRETE COVER IS ADEQUATE
CONCRETE COVER IS INADEQUATE

VAR: **MIX** **(R)**
LABEL: CONCRETE MIX DESIGN
VALUES: HIGH CEMENT CONTENT
LOW CEMENT CONTENT
HIGH AGGREGATES CONTENT
LOW AGGREGATES CONTENT
CONCRETE IS POORLY MIXED
MIX DESIGN IS ADEQUATE AND SAFE

VAR: **STRENGTH** **(S)**
LABEL: CONCRETE STRENGTH
VALUES: CONCRETE STRENGTH < SPECIFIED
CONCRETE STRENGTH > SPECIFIED

VAR: **SOIL** **(T)**
LABEL: SOIL TYPE
VALUES: COLLAPSIBLE SOIL
WELL CONFINED SOIL
POORLY MADE GROUND
EXPANSIVE SOIL
CONSOLIDATED SOIL

VAR: **GWATER** **(U)**
LABEL: GROUND WATER QUALITY
VALUES: GROUND WATER UNDER PRESSURE
GROUND WATER IS CONTAMINATED WITH SULPHATES
GROUND WATER IS CONTAMINATED WITH CORROSIVE SALTS
GROUND WATER IS CONTAMINATED WITH SILICATES
GROUND WATER IS FLUCTUATING
GROUND WATER HAS NO NOTICIBLE EFFECT

VAR: **SOILCONT** **(V)**
LABEL: SOIL CHEMICAL ANALYSIS
VALUES: SOIL IS CONTAMINATED WITH SULFATES
SOIL IS CONTAMINATED WITH CORROSIVE SALTS
SOIL IS CLEAN AND FREE OF SALTS
SOIL IS CONTAMINATED WITH SILICATES

VAR: **MOMENT** **(W)**
LABEL: BENDING MOMENT CONSIDERATION
VALUES: POOR DISTRIBUTION OF BENDING MOMENT
ADEQUATE ESTIMATION OF BENDING MOMENT

VAR: **BEARCAP** **(X)**
LABEL: BEARING CAPACITY CONSIDERATION
VALUES: BEARING CAPACITY ESTIMATION IS INACCURATE
BEARING CAPACITY ESTIMATION IS SAFE AND ADEQUATE

VAR: **STEEL** **(Y)**
LABEL: REINFORCEMENT PROVISION
VALUES: BARS ARE NOT PLACED AS DESIGNED
STIRRUPS ARE POORLY PLACED
BARS ARE PROPERLY PLACED AND ADEQUATE
BARS ARE PLACED AS DESIGNED, BUT NOT ADEQUATE

VAR: **ENV** **(Z)**
LABEL: ENVIRONMENTAL CONDITIONS
VALUES: ATMOSPHERE POLLUTED WITH SULFUROUS GAS
MARINE ENVIRONMENT
HIGH WIND
HOT WEATHER
OCCURENCE OF HEAVY RAIN, OR SEASONAL VARIATION
NO EXPECTED EFFECT

VAR: **SLOC**
LABEL: LOCATION OF DEFECT IN A SLAB
VALUES: AT EDGE OF SLAB
AT MIDDLE OF SLAB
ALONG REINFORCEMENT

VAR: **CRAKWID** **(A')**
LABEL: CRACK WIDTH IN A BEAM
VALUES: WIDE
SPLITTING
SHALLOW

VAR: **CRAKLEN** **(B')**
LABEL: CRACK LENGTH IN A BEAM
VALUES: SHORT
VARYING IN LENGTH
RUNNING ALONG REINFORCEMENT

VAR: **CRAKDIR** **(C')**
LABEL: CRACK DIRECTION IN A BEAM
VALUES: VERTICAL CRACKS
INCLINED CRACKS
SURFACE CRAZING
RUNNING IN ALL DIRECTIONS
NON OF THE ABOVE

VAR: **BSYM** **(D')**
LABEL: BEAM SURFACE APPEARANCE
VALUES: EFFLORESCENCE AND DISCOLORATION OF BEAM
WHITE PATCHES AND STAINS WHEN DRY
RUST STAINS
NON OF THE ABOVE

VAR: **BCONC** **(E')**
LABEL: CONCRETE SURFACE CONDITION IN A BEAM
VALUES: SPALLING OF CONCRETE COVER
CONTINUOUS OR PARTIAL SPLITTING OF BEAM BOTTOM COVER
CONCRETE IS SOFT AND MUSHY WHEN DAMP
NON OF THE ABOVE

VAR: **BLOC** **(F')**
LABEL: LOCATION OF DEFECT IN A BEAM
VALUES: AT NEGATIVE MOMENT LOCATIONS
BETWEEN SUPPORT AND MOMENT INFLECTION (SHEAR ZONE)
AT RANDOM, AT ANY LOCATION
ALONG REINFORCEMENT, AT BEAM SIDE OR BOTTOM
ALONG BOTTOM REINFORCEMENT AT BEAM SIDE ONLY
NO LOCATION IS AFFECTED

VAR: **SHEAR** **(G')**
LABEL: SHEAR DESIGN CONSIDERATION
VALUES: POOR DISTRIBUTION OF SHEAR LOAD
ADEQUATE ESTIMATION OF SHEAR LOAD

VAR: **SERVICE** **(H')**
LABEL: SERVICE CONDITIONS
VALUES: STRUCTURE IS PRACTICING HIGHER LOADS THAN DESIGNED
NO SUSPECTED EVENT

VAR: **CRAKBEHV** **(A")**
LABEL: BEHAVIOR OF CRACK IN A COLUMN
VALUES: SPLITTING CRACKS
LOCALLY CONCENTRATED CRACKS
NON OF THE ABOVE

VAR: **CCRACK** **(B")**
LABEL: CRACK DIRECTION IN A COLUMN
VALUES: VERTICAL AND/OR HORIZONTAL CRACKS
ONLY VERTICAL CRACKS
NON OF THE ABOVE

VAR: **CSYM** **(C")**
LABEL: COLUMN SURFACE APPEARANCE
VALUES: EFFLORESCENCE AND DISCOLORATION OF BEAM
WHITE PATCHES AND STAINS WHEN DRY
RUST STAINS
NON OF THE ABOVE

VAR: **CCONC** **(D")**
LABEL: CONCRETE SURFACE CONDITION IN A COLUMN
VALUES: SPALLING OF CONCRETE COVER
PEALING OF CONCRETE COVER AT INTERVALS
NON OF THE ABOVE

VAR: **CLOC** **(E")**
LABEL: LOCATION OF DEFECT IN A COLUMN
VALUES: AT RANDOM, AT ANY LOCATION
ANY LOCATION ALONG REINFORCEMENT
AT INTERVALS ALONG THE COLUMN
NO LOCATION IS AFFECTED

VAR: **COL** **(F")**
LABEL: COLUMN SLENDERNESS RATIO
VALUES: COLUMN SLENDERNESS RATIO IS < ALLOWABLE
COLUMN SLENDERNESS RATIO IS SAFE

VAR: **CAUSE**
LABEL: FACTOR CAUSING THE DEFECT

SLAB HEAVING
S11 = "STRUCTURAL FAILURE OF SLAB DUE TO POOR DESIGN"
S12 = "IMPROPER PLACEMENT OR LACK OF REINFORCEMENT DURING CONSTRUCTION"
S13 = "EXISTENCE OF EXPANSIVE SOIL NOT CONSIDERED IN DESIGN"

SLAB SETTLEMENT
S21 = "EXISTENCE OF COLLAPSIBLE SOIL OR CAVITIES THAT WERE IGNORED DURING DESIGN"
S22 = "POOR DETAILING OF BARS RESULTING IN RESTRAINING CORNERS AND IMPOSING JOINTS FUNCTION"
S23 = "MISESTIMATION OF LOAD DURING DESIGN AND/OR UNDER ESTIMATION OF SOIL BEARING CAPACITY"
S24 = "POOR CONCRETE QUALITY RESULTING IN STRUCTURAL INADEQUACY"
S25 = "POOR REINFORCEMENT DESIGN OR DETAILING RESULTING IN RESTRAINED CORNERS, AND DEVELOPMENT OF A RIGID FRAMING SENSITIVE TO SETTLEMENT/DEFLECTION DELAMINATION"

SULPHATE ATTACK

S31 = "SULPHATE ATTACK DUE TO USE OF WRONG CEMENT TYPE, WHERE EXPOSURE CONDITIONS TO SULPHATES NECESSITATE THE USE OF SULPHATES RESISTANT CEMENT"

S32 = "SULPHATE ATTACK DUE TO SOIL CONTAMINATION NOT ALLOWED FOR DURING DESIGN WITH PROPER PROOFING MEASURES"

S33 = "RISE OF CONTAMINATED GROUND WATER DEPOSITING SULPHATES UNDER THE SLAB"

S34 = "USE OF CONTAMINATED AGGREGATES RESULTED IN POOR QUALITY CONCRETE LIABLE FOR SULPHATE ATTACK"

S35 = "PRODUCTION OF LOW STRENGTH, POROUS CONCRETE DURING CONSTRUCTION INHIBITED THE ATTACK OF SULPHATE SALTS"

SLAB CORROSION

S41 = "CORROSION DUE TO SOIL CONTAMINATION NOT PROTECTED AGAINST WITH COUNTER MEASURES"

S42 = "CORROSION DUE TO RISE OF CONTAMINATED GROUND WATER DEPOSITING SALTS UNDER THE SLAB"

S43 = "CORROSION DUE TO USE OF POOR QUALITY CONCRETE LIABLE TO CORROSION"

S44 = "CORROSION DUE TO FAILURE TO PROVIDE SUFFICIENT CONCRETE COVER"

S45 = "CORROSION DUE TO USE OF POOR QUALITY AGGREGATES THAT INITIATED CONCRETE CORROSION"

SLAB ALKALI-AGGREGATE REACTION

S51 = "ALKALI-AGGREGATE REACTION DUE TO USE OF CONTAMINATED AGGREGATES"

S52 = "ALKALI-AGGREGATE REACTION DUE POOR CONCRETE QUALITY AND CONTAMINATION FROM GROUND SOIL NOT PROTECTED AGAINST"

S53 = "ALKALI-AGGREGATE REACTION DUE TO USE OF POOR QUALITY CONCRETE LIABLE TO CHEMICAL ATTACK FROM THE GROUND WATER"

S54 = "ALKALI-AGGREGATE REACTION DUE TO USE OF HIGH CEMENT CONTENT IN CONCRETE LIABLE TO CHEMICAL ATTACK FROM THE MODERATELY CONTAMINATED AGGREGATES"

BEAM FLEXURAL CRACKING

B11 = "STRUCTURAL FAILURE OF BEAM DUE TO POOR DESIGN"

B12 = "IMPROPER PLACEMENT OR LACK OF REINFORCEMENT DURING CONSTRUCTION"

B13 = "EXISTENCE OF POOR SOIL NOT CONSIDERED IN DESIGN"

B14 = "OVERLOADING OF THE STRUCTURE NOT CONSIDERED IN DESIGN"

BEAM SHEAR CRACKING

B21 = "SHEAR FAILURE OF BEAM DUE TO POOR DESIGN"

B22 = "SHEAR FAILURE OF BEAM DUE TO USE OF POOR QUALITY CONCRETE"

B23 = "OVERLOADING OF THE STRUCTURE NOT CONSIDERED IN DESIGN RESULTED IN OVERSTRESSING THE MEMBERS SHEAR STRENGTH"

BEAM SULPHATE ATTACK

B31 = "SULPHATE ATTACK DUE TO USE OF WRONG CEMENT TYPE IN A HARSH ENVIRONMENT LIABLE FOR DETERIORATION"

B32 = "USE OF CONTAMINATED AGGREGATES RESULTED IN POOR QUALITY CONCRETE LIABLE FOR SULPHATE ATTACK "
B33 = "PRODUCTION OF POOR QUALITY POROUS CONCRETE LIABLE FOR SULPHATE ATTACK"

BEAM CORROSION
B41 = "CORROSION DUE TO USE OF POOR QUALITY CONCRETE LIABLE TO CORROSION"
B42 = "CORROSION DUE TO FAILURE TO PROVIDE SUFFICIENT CONCRETE COVER"
B43 = "CORROSION DUE TO USE OF POOR QUALITY AGGREGATES THAT INITIATED CONCRETE CORROSION"

BEAM SHRINKAGE CRACKING
B51 = "SHRINKAGE CRACKING DUE TO INSUFFICIENT CURING WHILE CONSTRUCTION"
B52 = "SHRINKAGE CRACKING DUE TO USE OF POOR QUALITY AGGREGATES DURING CONSTRUCTION"
B53 = "SHRINKAGE CRACKING DUE TO ADDING HIGH WATER CONTENT DURING CONSTRUCTION"

BEAM BOND FAILURE
B61 = "POOR WORKMANSHIP RESULTED IN POORLY SPLICED REINFORCEMENT DURING CONSTRUCTION"
B62 = "POOR ESTIMATION OF BARS DEVELOPMENT LENGTH OR MEMBER IS CONGESTED WITH REBARS"
B63 = "PRODUCTION OF LOW STRENGTH CONCRETE"

COLUMN BUCKLING
C11 = "STRUCTURAL FAILURE OF COLUMN DUE TO POOR DESIGN"
C12 = "COLUMN BUCKLING DUE TO IMPROPER PLACEMENT OR LACK OF REINFORCEMENT DURING CONSTRUCTION"
C13 = "COLUMN BUCKLING DUE TO OVERLOADING OF THE STRUCTURE NOT CONSIDERED IN DESIGN"

COLUMN CORROSION
C21 = "CORROSION DUE TO USE OF POOR QUALITY CONCRETE LIABLE TO CORROSION"
C22 = "CORROSION DUE TO FAILURE TO PROVIDE SUFFICIENT CONCRETE COVER"
C23 = "CORROSION DUE TO USE OF POOR QUALITY AGGREGATES THAT INITIATED CONCRETE CORROSION"

5.2 Decision Trees

At this stage a sufficient familiarity with the domain is achieved and the next step is to simulate the diagnosis process and draw the relations between the collected information. Decision trees are the means of representing the relations between the various problems' attributes. The aim is to draw how an expert arrives at a decision through looking at different aspects of a problem.

In a decision tree, each variable represents a node, while the values each variable may possess indicate different decision paths. In other terms, each node can be a question with one or more answers radiating from it. The process of developing and drawing the decision trees for each single sub-problem searching through all possible decision values is troublesome and not practical. This is due to the fact that the search space is far too large to draw a comprehensive tree for the expert system. Yet, the concept is very helpful to visualize and explain, how an expert analyzes a problem, and how an inference engine searches through the knowledge base. The general rule is, simple decision trees are drawn, but variation according to different decision values are assumed based on these trees. Then we can imagine the search space growing an increment at a time, as the inference engine moves from a node to the next looking for a solution.

Consequently, general decision trees are drawn to depict the different search routines in the system. A general decision tree illustrates a specific split route the diagnosis process may follow in case certain decision values are chosen. For instance, in case symptoms variables lead to a sub-goal named (corrosion in a slab on grade), the search path is whole directed to the corrosion diagnosis routine. Yet, if some input values refer to some other problem, as well, the search path will tackle both problems, each route at a time.

Moreover, split decision trees are drawn to explain each independent search path among different diagnostic routines. Each tree assumes that a specific problem is addressed and depicts its related variables. The variables are those considered to reach a diagnostic decision. As a result, separate decision trees are developed for each defect case in a specific member, i.e., slab settlement, slab heaving, beam flexural cracking, . . . and so forth.

Tables 5.2, 5.3, 5.4, and 5.5 are developed specifically to facilitate the understanding of variables' relations and draw these relations easily in decision trees format. Each table represents the different attributes pertaining to a specific problem in a member and leading to a certain contributing factor. As a result, each problem in a member is associated with its interrelating variables that will lead the diagnosis process to yield a certain decision.

The output of these tables is displayed on decision trees i.e., the relations are drawn together searching through the decision variables. For example, {a corrosion in a slab on grade} problem may be detected by the

Table 5.2 Diagnosis of Defect Cases in Grade Slabs.

	G. Slab Heaving			G.Slab S.Attack			G.Slab Corrosion				G.Slab A.Agg.React			
SCRACK (A)				A3	A3	A3	A4	A4	A4	A4	A2	A2	A2	A2
SSYM (B)	B1/B2	B1/B2	B1/B2	B4	B4	B4					B3	B3	B3	B3
STIME (C)	C1	C1	C1								C3	C3	C3	C3
SRELATE (D)	D1	D1	D1											
SAPPER (E)				E1/E2	E1/E2	E1/E2	E3	E3	E3	E3	E4	E4	E4	E4
SCONC (F)				F3	F3	F3	F4	F4	F4	F4	F2	F2	F2	F2
POT (G)							G2	G2	G2	G2				
CL (H)							H2	H2	H2	H2				
PH (I)							*I2	*I2	*I2	*I2				
CO (J)							*J2	*J2	*J2	*J2				
SL (K)				K2	K2	K2								
PERM (L)							L2	L1	LI	LI		L2	LE	
QUALITY (M)							M3	*M3	*M3	*M3				
AGG (N)				*N4	*N4	N4	*N3	N3	*N3	*N3	N1	*N1	*N1	N1
CEMENT (O)				O2	O2	O2								
WC (P)														
COVER (Q)														
MIX (R)											*R1			R1
STRENGTH (S)														
SOIL (T)	*T4	T4	T4											
GWATER (U)				*U2	U2	*U2	*U3	*U3	U3	*U3		*U4	U4	
SOILCONT (V)				V1	*V1	*V1	*V2	*V2	*V2	V2		V4	*V4	
MOMENT (W)	W1	W2	W1											
BEARCAP (X)														
STEEL (Y)		Y2	Y4											
ENV (Z)		Z5	Z5											
CAUSE (Dec)	11	12	13	32	33	34	41	42	43	44	51	52	53	54

Table 5.3 Diagnosis of Defect Cases in Slabs.

	Slab Settlement				Slab Sulphate Attack		Slab Corrosion		Slab A.Agg.React	
SCRACK (A)					A3	A3	A4	A4	A2	A2
SSYM (B)	B2	B2	B2	B2	B4	B4			B3	B3
STIME (C)	C3	C3	C3	C3					C3	C3
SRELATE (D)	D2/D3	D2/D3	D2/D3	D2/D3						
SAPPER (E)					E1/E2	E1/E2	E3	E3	E4	E4
SCONC (F)	F5	F5	F5	F5	F3	F3	F4	F4	F2	F2
POT (G)							G2	G2		
CL (H)							H2	H2		
PH (I)							*I2	*I2		
CO (J)							*J2	*J2		
SL (K)					K2	K2				
PERM (L)							L2	L1		
QUALITY (M)							M3	*M3		
AGG (N)						N4	*N3	N3	N1	N1
CEMENT (O)					*O2	O2				
WC (P)										
COVER (Q)										
MIX (R)									*R1	R1
STRENGTH (S)				S1						
SOIL (T)	T1	*T1	*T1	*T1						
GWATER (U)										
SOILCONT (V)										
MOMENT (W)		W2	W1	W2						
BEARCAP (X)	X1	X2	X1	X2						
STEEL (Y)		Y2	Y4	Y3						
ENV (Z)					Z1/Z2					
CAUSE (Dec)	21	22	23	24	31	34	41	42	51	54

Table 5.4 Diagnosis of Defect Cases in Beams.

	Beam Flexural Cracking				Beam Shear Cracking			Beam Sulphate Attack			Beam Corrosion			Beam Shrinkage Cracking			Beam Bond Failure		
CRAKWID (A')	A'1	A'1	A'1	A'1	A'1	A'1	A'1				A'2	A'2	A'2	A'3	A'3	A'3	A'2	A'2	A'2
CRAKLEN (B')	B'2	B'2	B'2	B'2							B'3	B'3	B'3	B'1	B'1	B'1			
CRAKDIR (C')	C'1	C'1	C'1	C'1	C'2	C'2	C'2	C'3	C'3	C'3				C'4	C'4	C'4			
BSYM (D')									D'1/D'2		D'3	D'3	D'3				*D'3	*D'3	*D'3
BCONC (E')								E'3	E'3	E'3	E'1	E'1	E'1				E'2	E'2	E'2
BLOC (F')	F'1	F'1	F'1	F'1	F'2	F'2	F'2	F'3	F'3	F'3	F'4	F'4	F'4	F'3	F'3	F'3	F'5	F'5	F'5
POT (G)											G2	G2	G2				G1	G1	G1
CL (H)											H2	H1	H2						
PH (I)											I2	I2	I1						
CO (J)											J2	J2	J1						
SL (K)								K2	K2	K2									
PERM (L)											L2	L1	L1						
QUALITY (M)										M3	M3	*M3	*M3	M2	M1	M2			
AGG (N)								*N4	N4	*N4	*N3	*N3	N3	N5	N2	*N2			
CEMENT (O)								*O2	O2	O2									
WC (P)														P3		P4			
COVER (Q)												Q2							
MIX (R)														R6	*R6	R6			
STRENGTH (S)					S2	S1	S2	S1	S1	S1									S1
SOIL (T)	T2	T2	*T2	T2															
MOMENT (W)	W1	W2	W1	W2													W2	W1	W2
BEARCAP (X)																			
SHEAR (W')					W'1	W'2	W'2												
SERVICE (X')	X'2	X'2	X'2	X'1	X'2	X'2	X'1												
STEEL (Y)	Y4	Y1	Y4	Y3	Y4	Y3	Y3										Y1	Y4	Y3
ENV (Z)								Z1/Z2		Z1/Z2				Z3/Z4		Z3/Z4			
CAUSE (Dec)	B11	B12	B13	B14	B21	B22	B23	B31	B32	B33	B41	B42	B43	B51	B52	B53	B61	B62	B63

Table 5.5 Diagnosis of Defect Cases in Columns.

	Column Buckling			Column Corrosion		
CRAKBEHV (A")	A"2	A"2	A"2	A"1	A"1	A"1
CCRACK (B")	B"2	B"2	B"2	B"1	B"1	B"1
CCONC (D")	D"2	D"2	D"2	D"1	D"1	D"1
SAPPER (E)				E3	E3	E3
CLOC (E")	E"3	E"3	E"3	E"2	E"2	E"2
POT (G)				G2	G2	G2
CL (H)				H2	H1	H2
PH (I)				I2	I2	I1
CO (J)				J2	J2	J1
PERM (L)				L2	L1	L1
QUALITY (M)				M3	*M3	*M3
AGG (N)				*N3	*N3	N3
COVER (Q)					Q2	
STRENGTH (S)	S1	S2	S2			
SOIL (T)						
MOMENT (W)						
BEARCAP (X)						
SERVICE (H')	H'2	H'2	H'1			
COL (F")	F"1	F"2	F"2			
STEEL (Y)	Y4	Y1	Y3/Y2			
CAUSE (Dec)	C11	C12	C13	C21	C22	C23

aid of the variables *SCRACK*, *SAPPER*, or *SCONC*. For the corrosion to be ascertained, chemical analysis is a must. So, the variables, *POT*, and *CL* or (*PH* and *CO*) are called. These variables will decide also whether corrosion is due to {chlorides or carbonates}. If the case is positive, then the corrosion may be due to either external or internal factors. To find out if the cause is internal, the variables *PERM*, *QUALITY*, and *AGG* are tested. Yet, the cause of deterioration may be attributable to an external agent. So the variables *GWATER*, and *SOILCONT* are investigated. For cases where corrosion is not traced to both external or internal actions, the concrete cover must be checked. The variable *COVER* provides this service. Digesting the values assigned to these variables, the diagnosis process decides the cause and picks its value from within the goal variable *CAUSE*.

Fig 5.3 to Fig 5.20 depict the set of developed decision trees for each problem included in the domain of this study. In Fig 5.21 a detailed decision tree for corrosion in grade slabs is drawn.

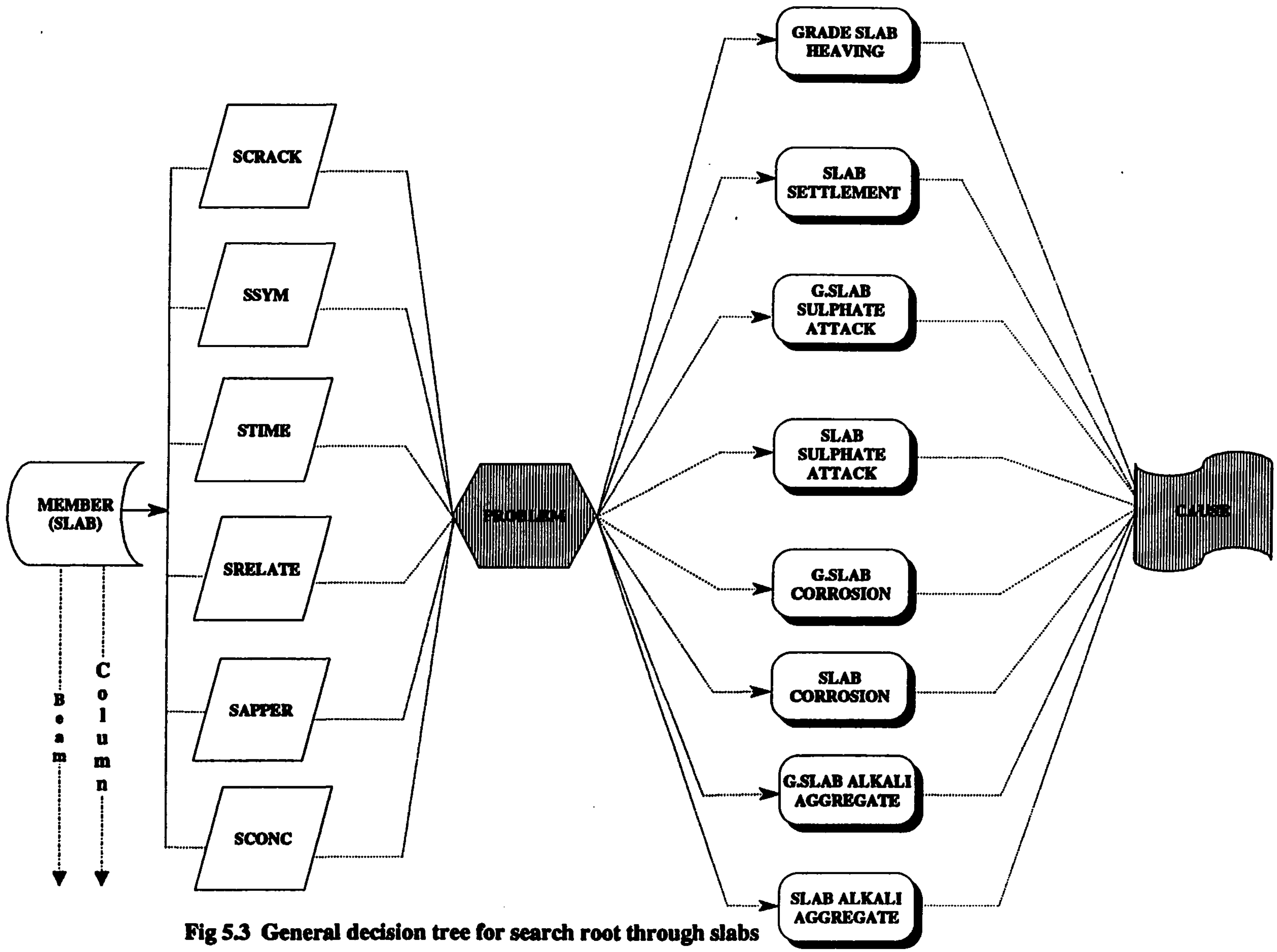


Fig 5.3 General decision tree for search root through slabs

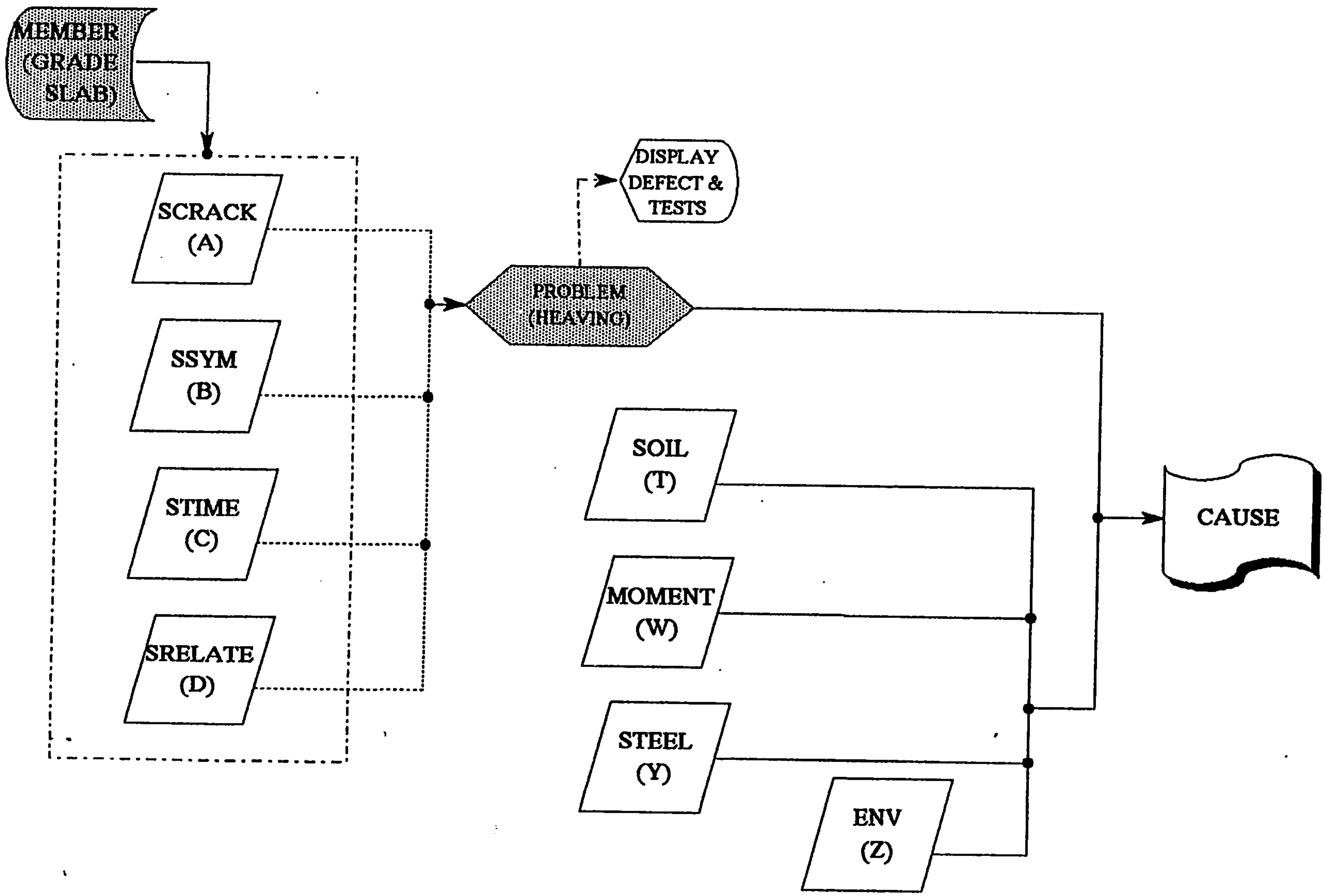


Fig 5.4 Decision Tree for Heaving in Grade Slab

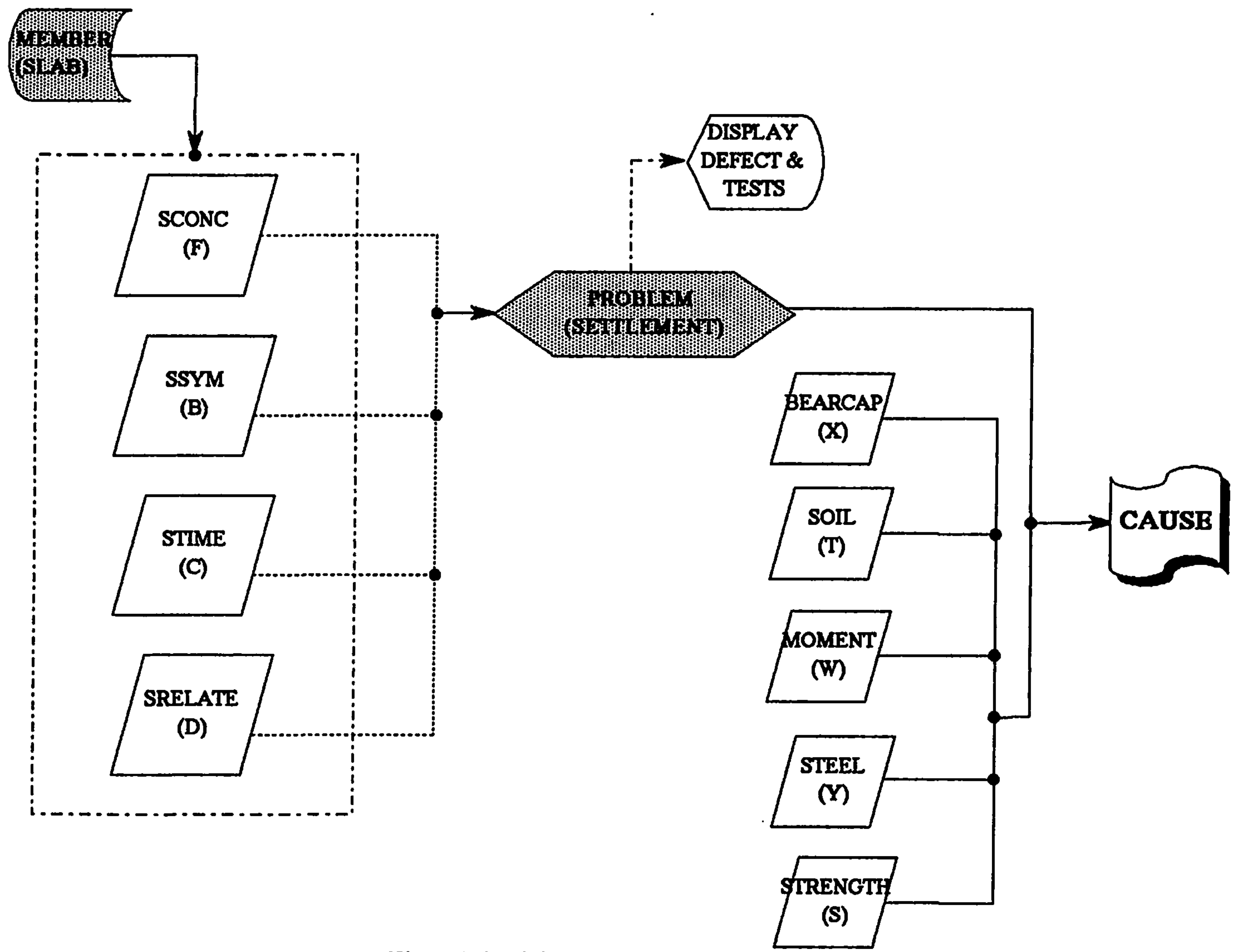


Fig 5.5 Decision Tree for Settlement of Slab

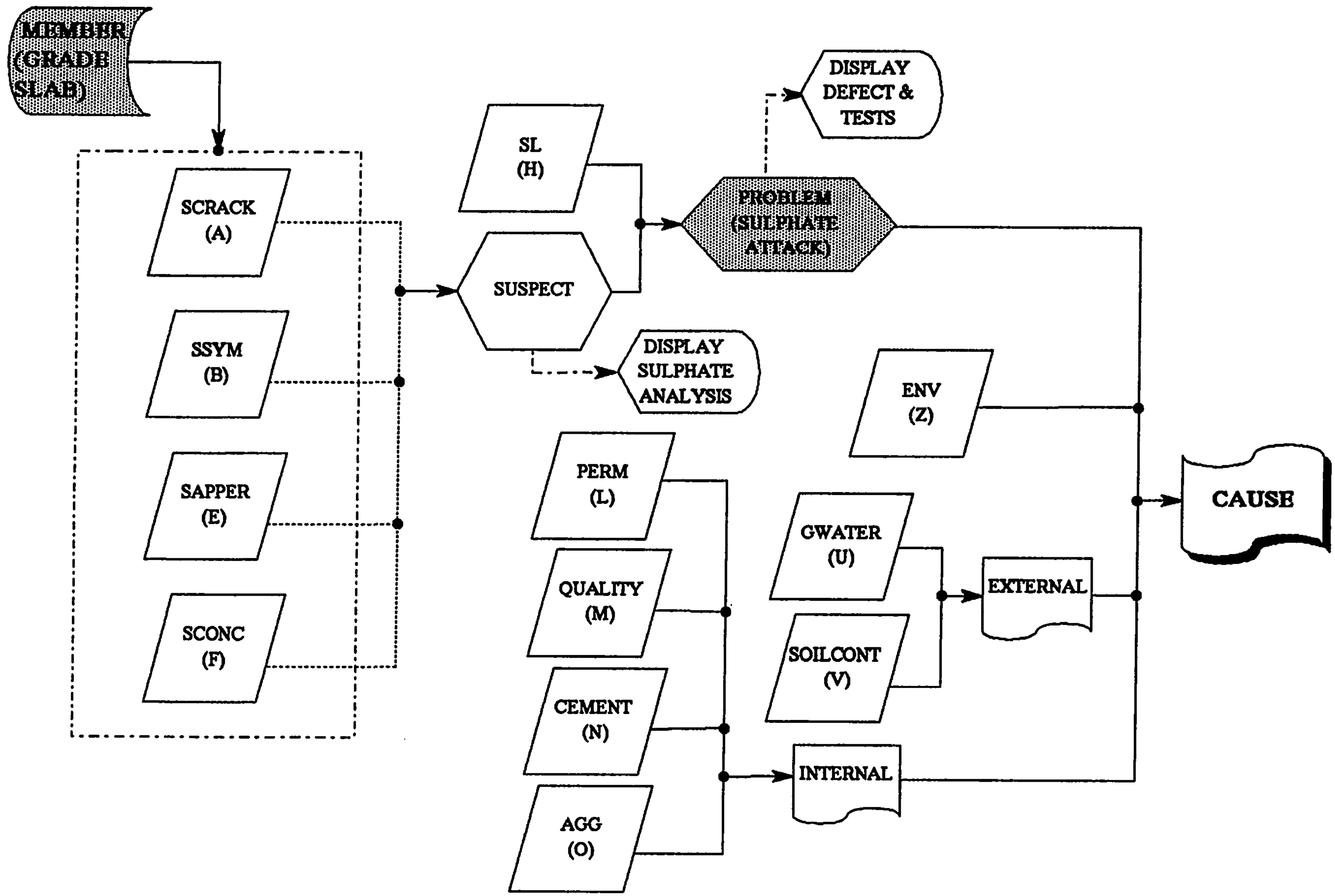


Fig 5.6 Decision Tree for Sulphate Attack in Grade Slab

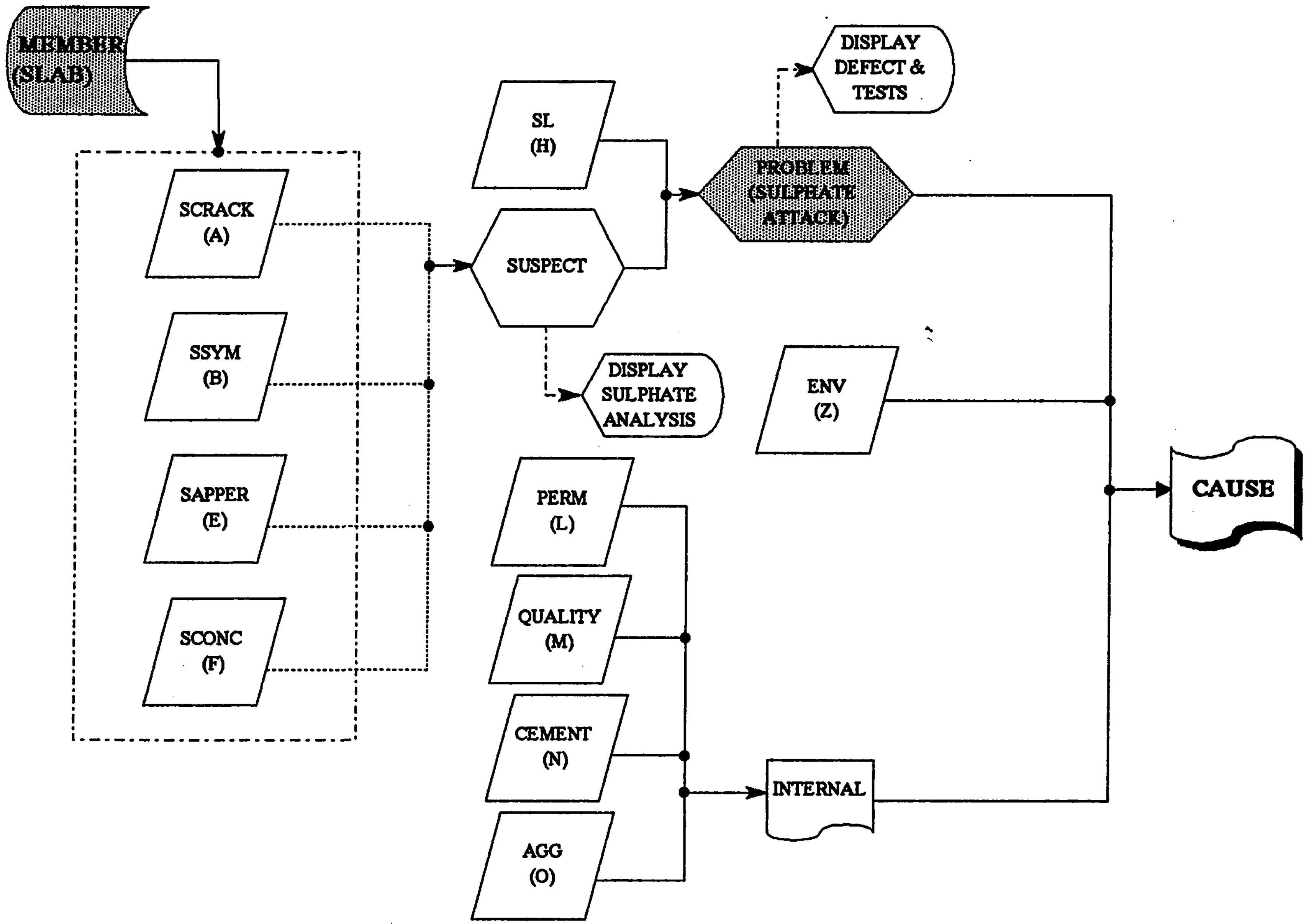


Fig 5.7 Decision Tree for Sulphate Attack in Slab

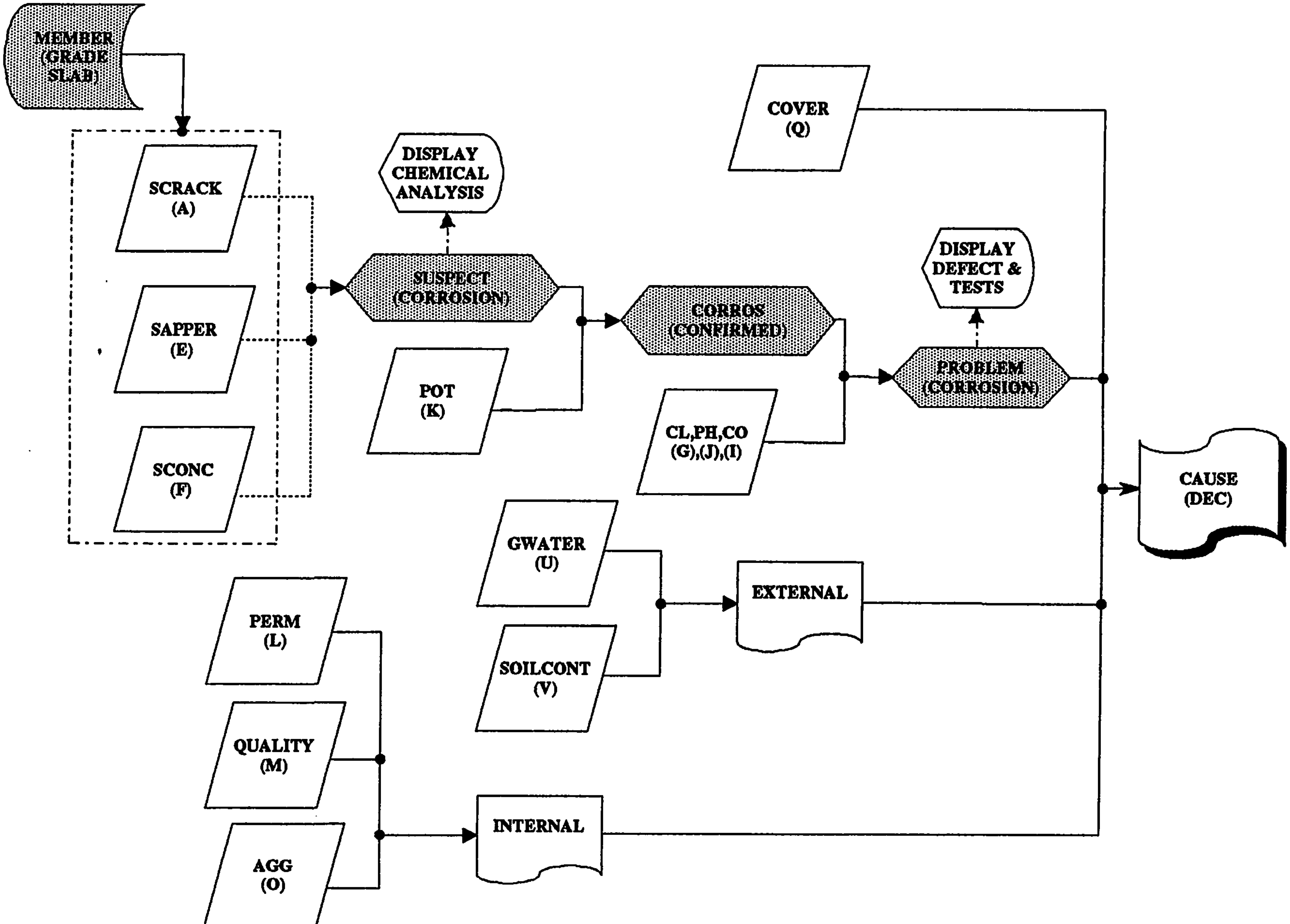


Fig 5.8 Decision tree for corrosion on g.slab

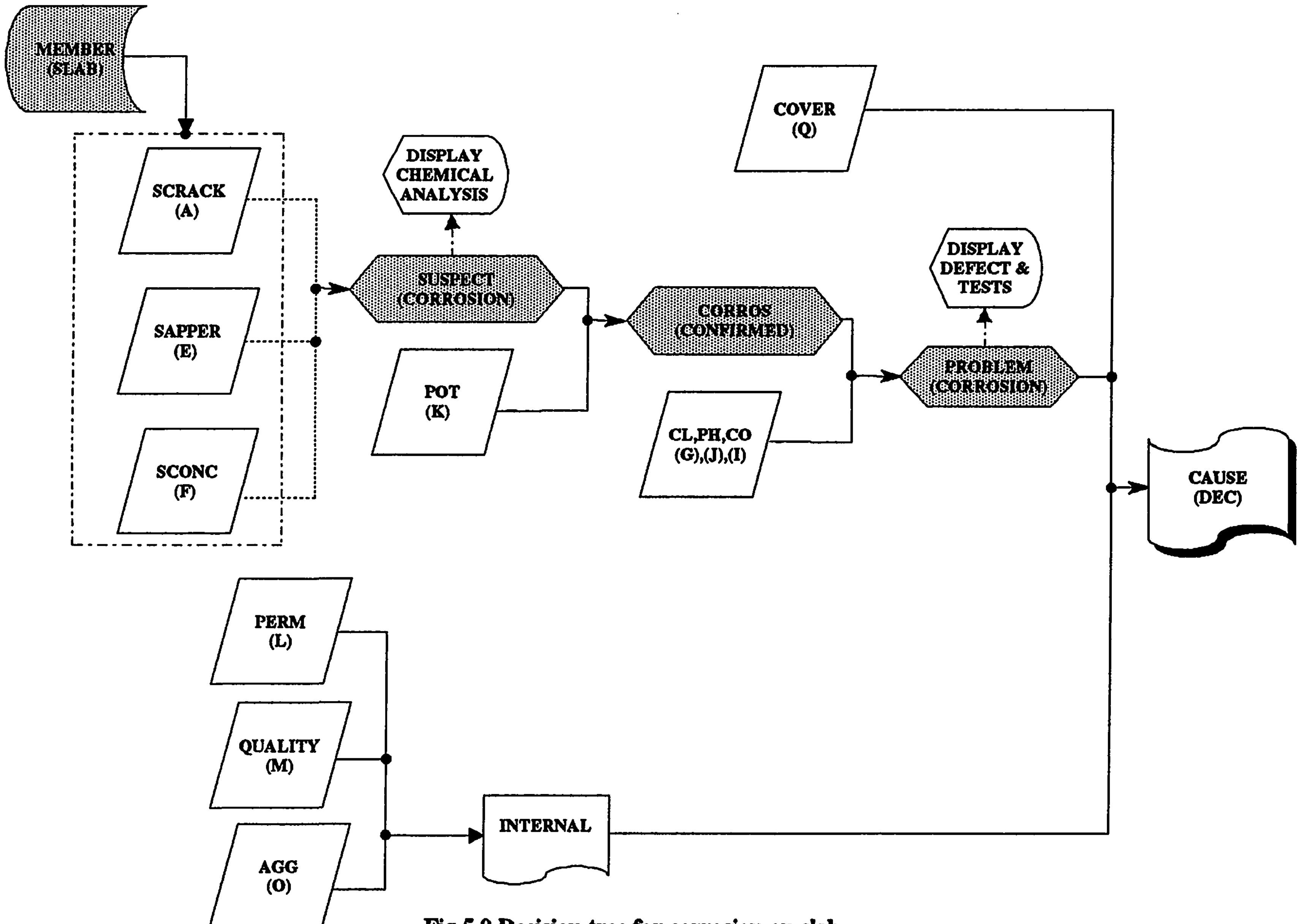


Fig 5.9 Decision tree for corrosion on slab

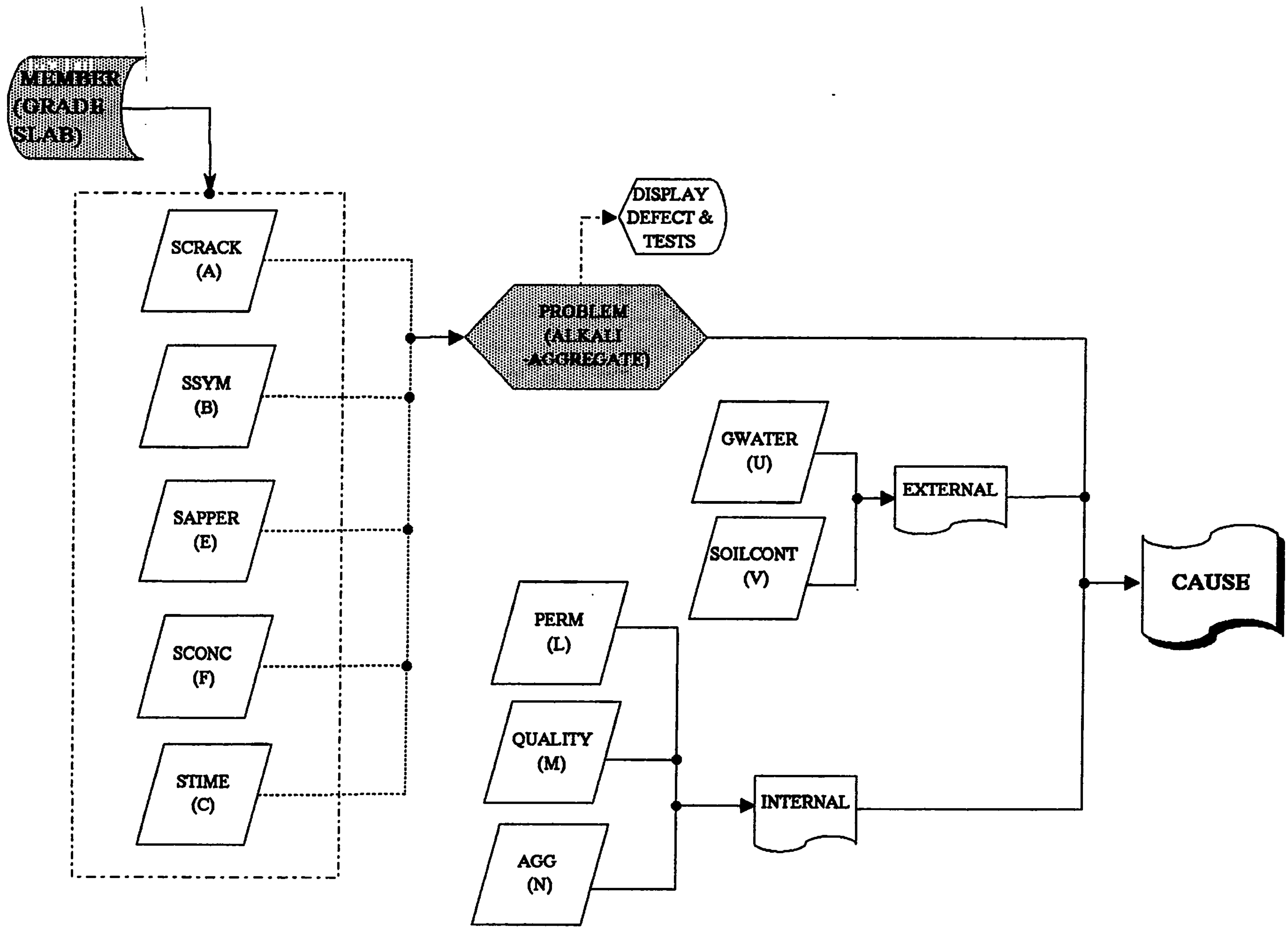


Fig 5.10 Decision Tree for Alkali-Aggregate Reaction in Grade Slab

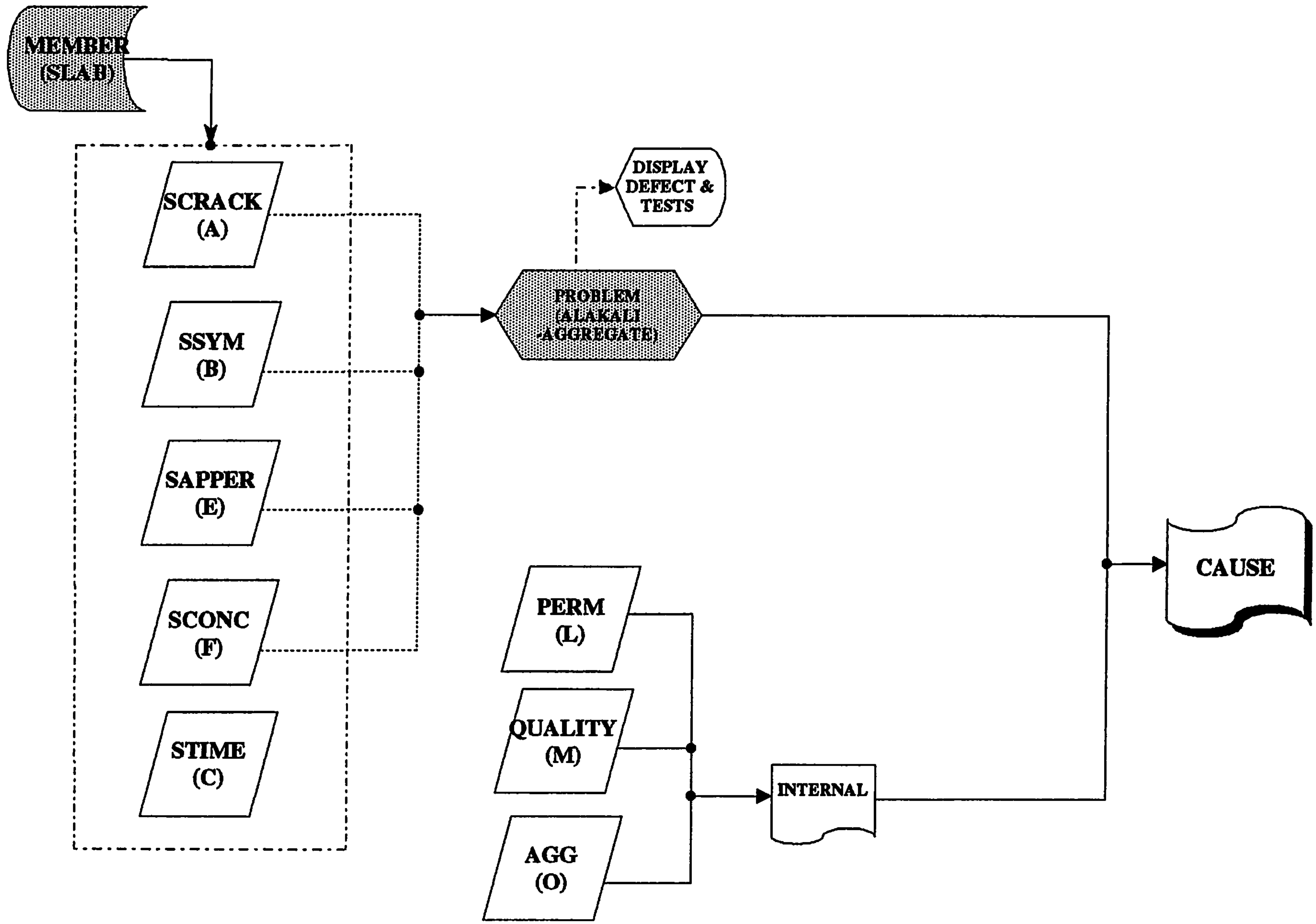


Fig 5.11 Decision tree for alkali-aggregate reaction on slab

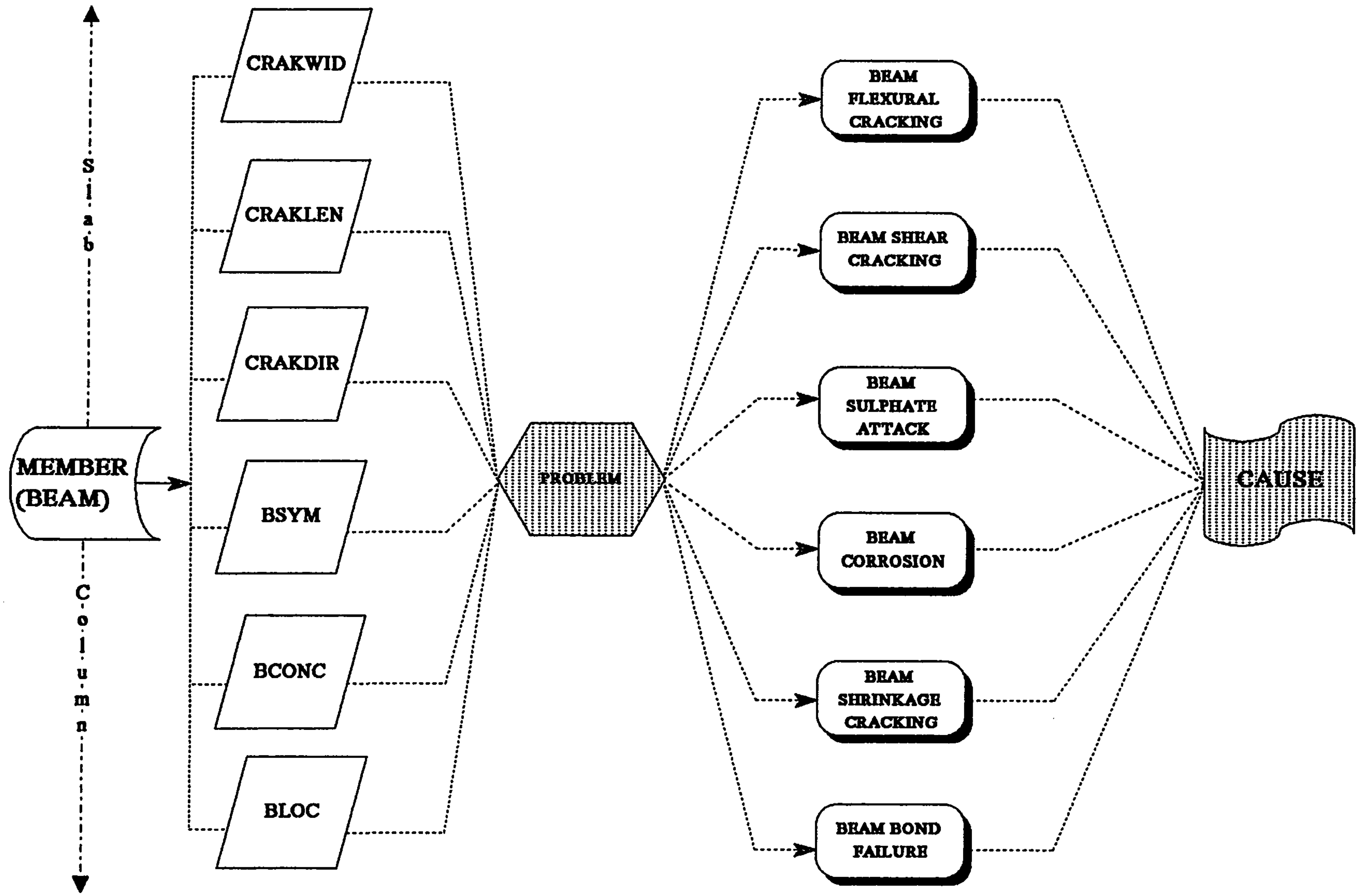


Fig 5.12 General Decision Tree for Search Root Through Beams

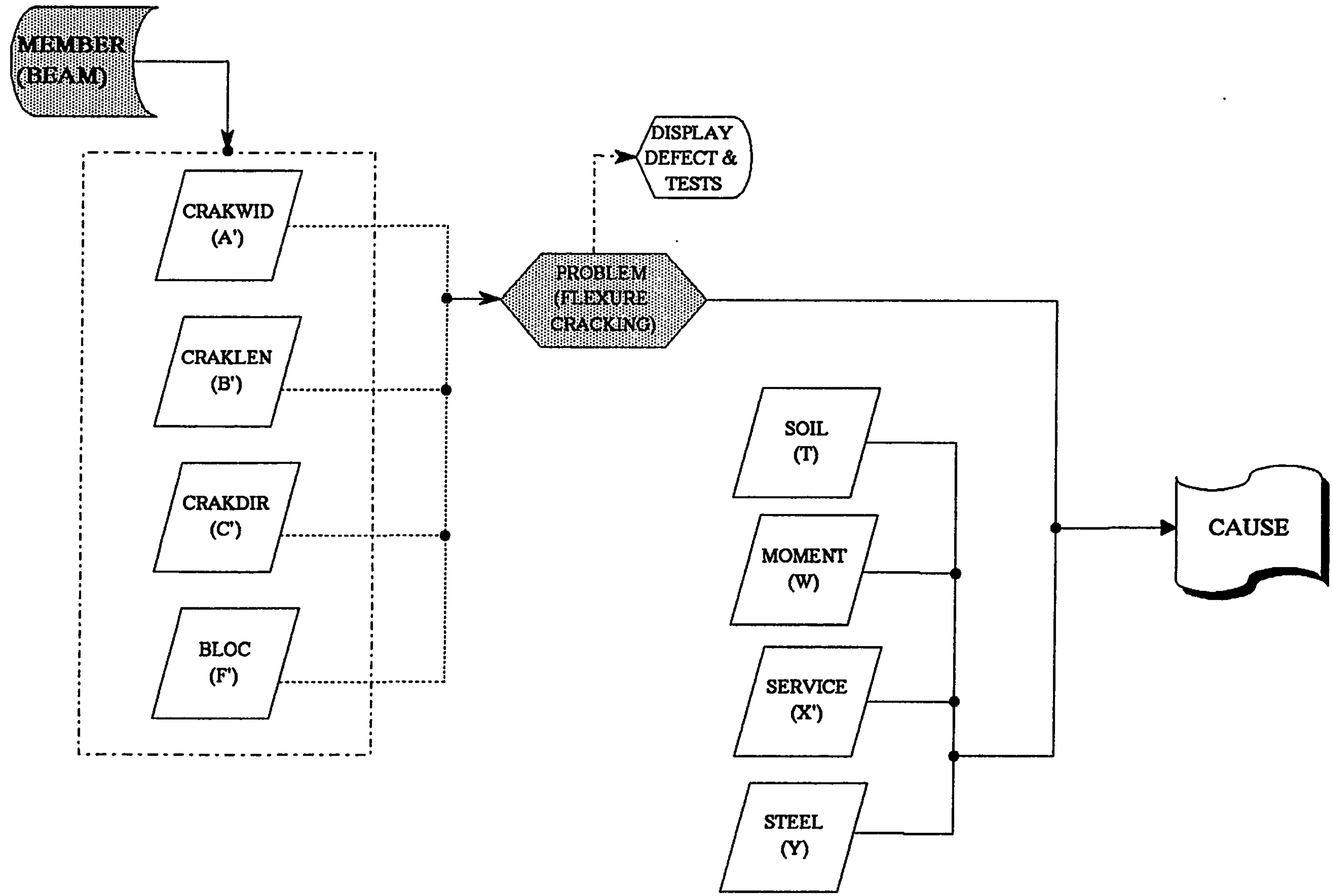


Fig 5.13 Decision Tree for Flexure in Beams

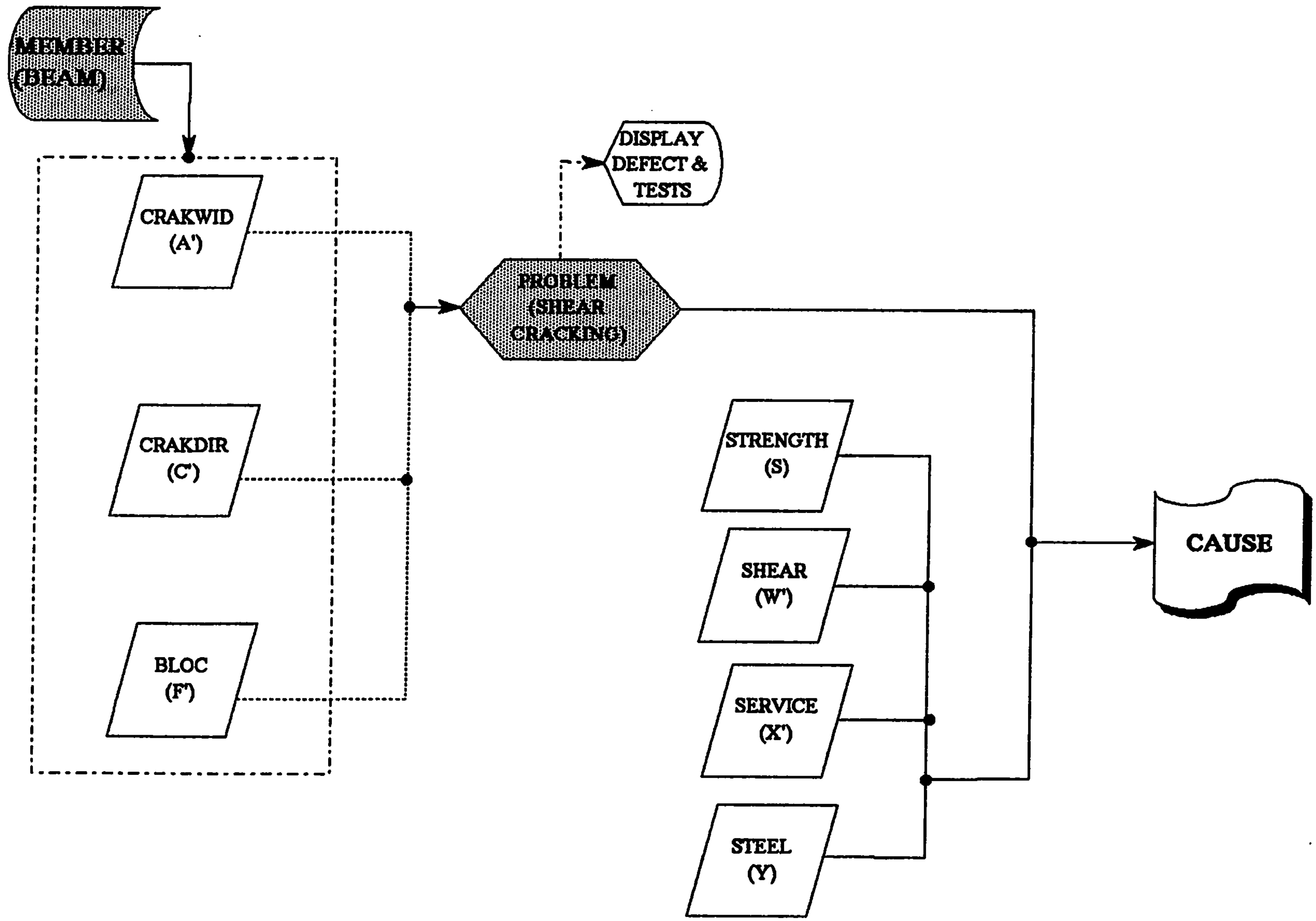


Fig 5.14 Decision Tree for Shear in Beams

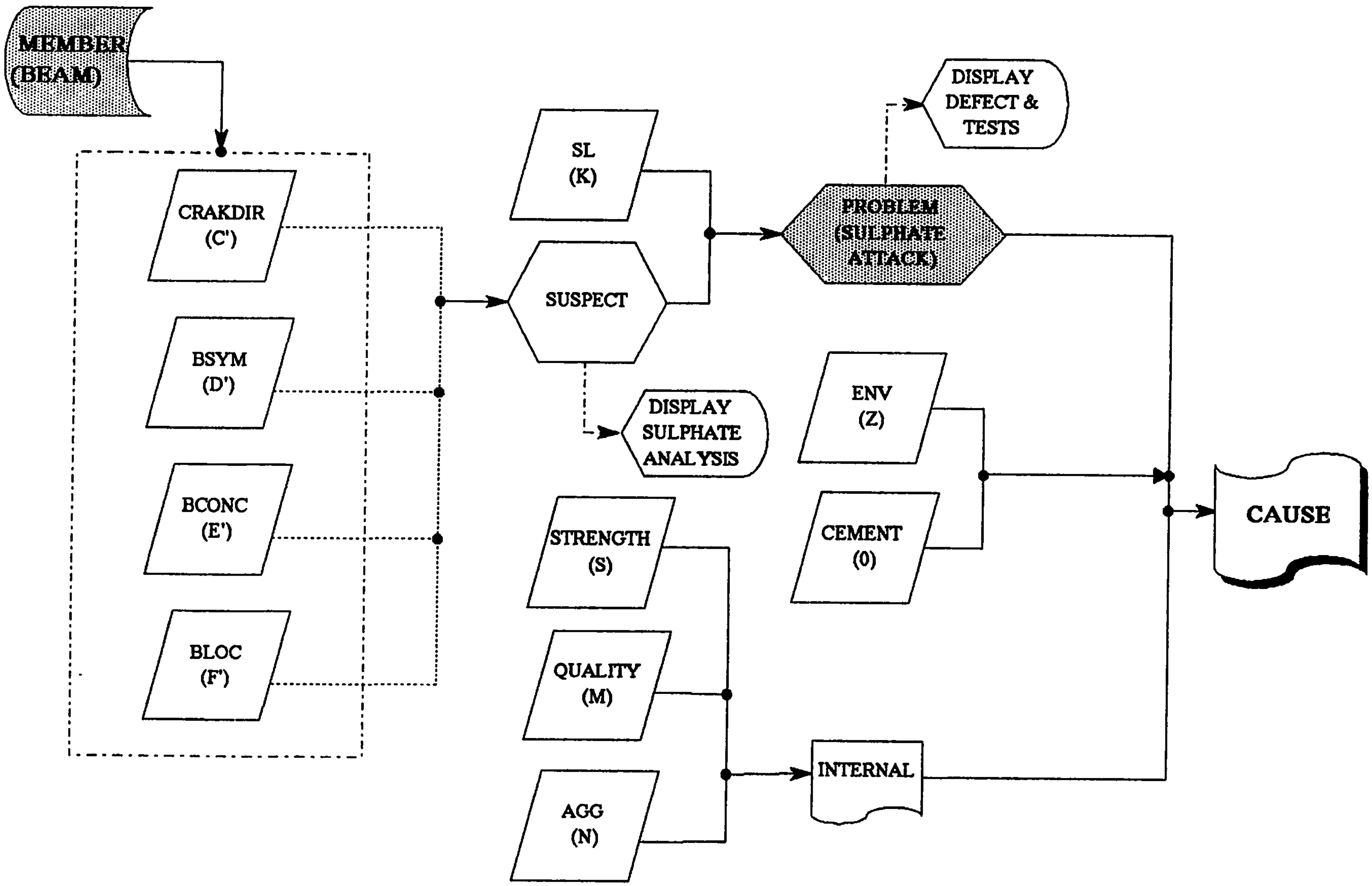


Fig 5.15 Decision Tree for Sulphate Attack in Beams

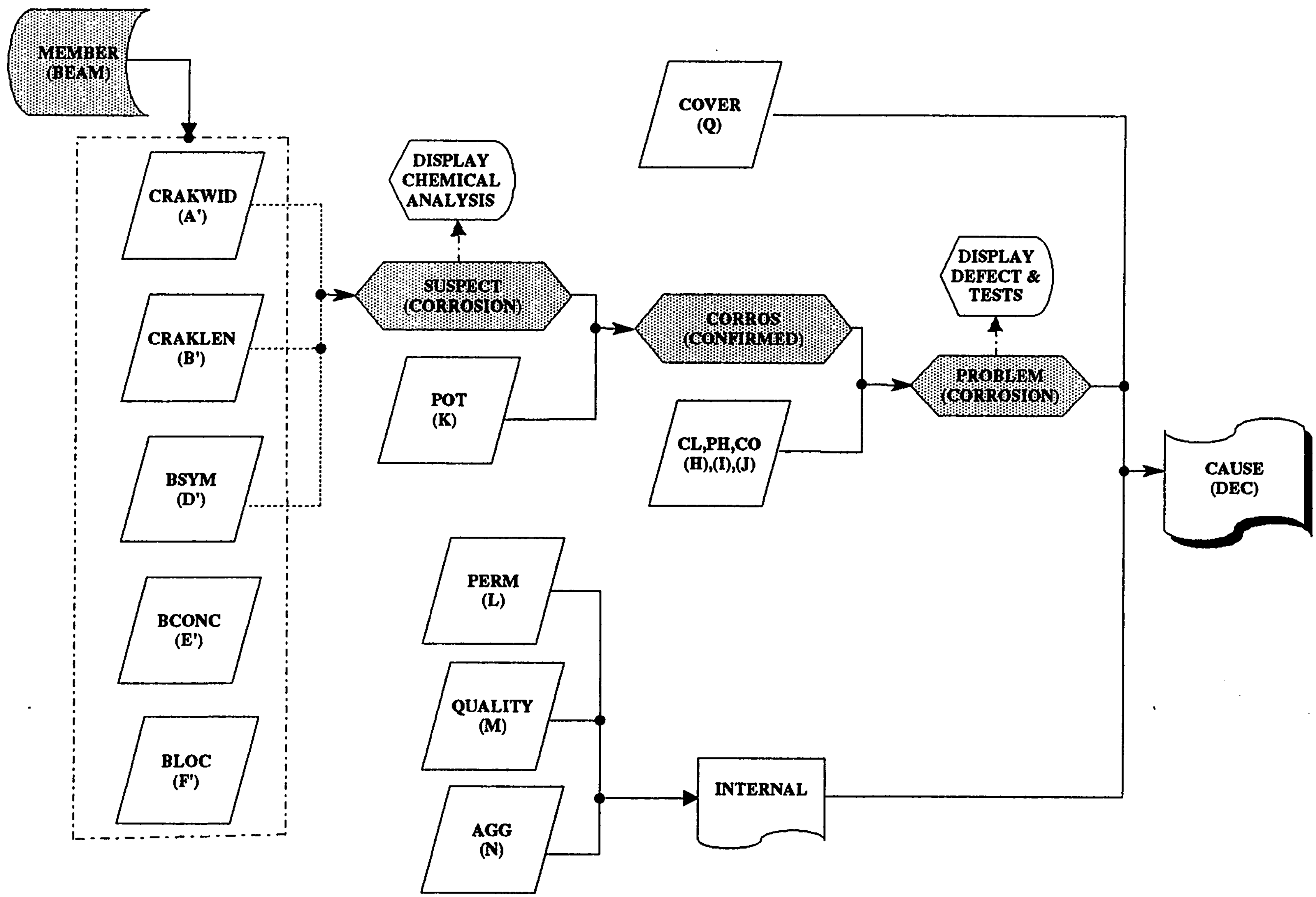


Fig 5.16 Decision tree for corrosion in beams

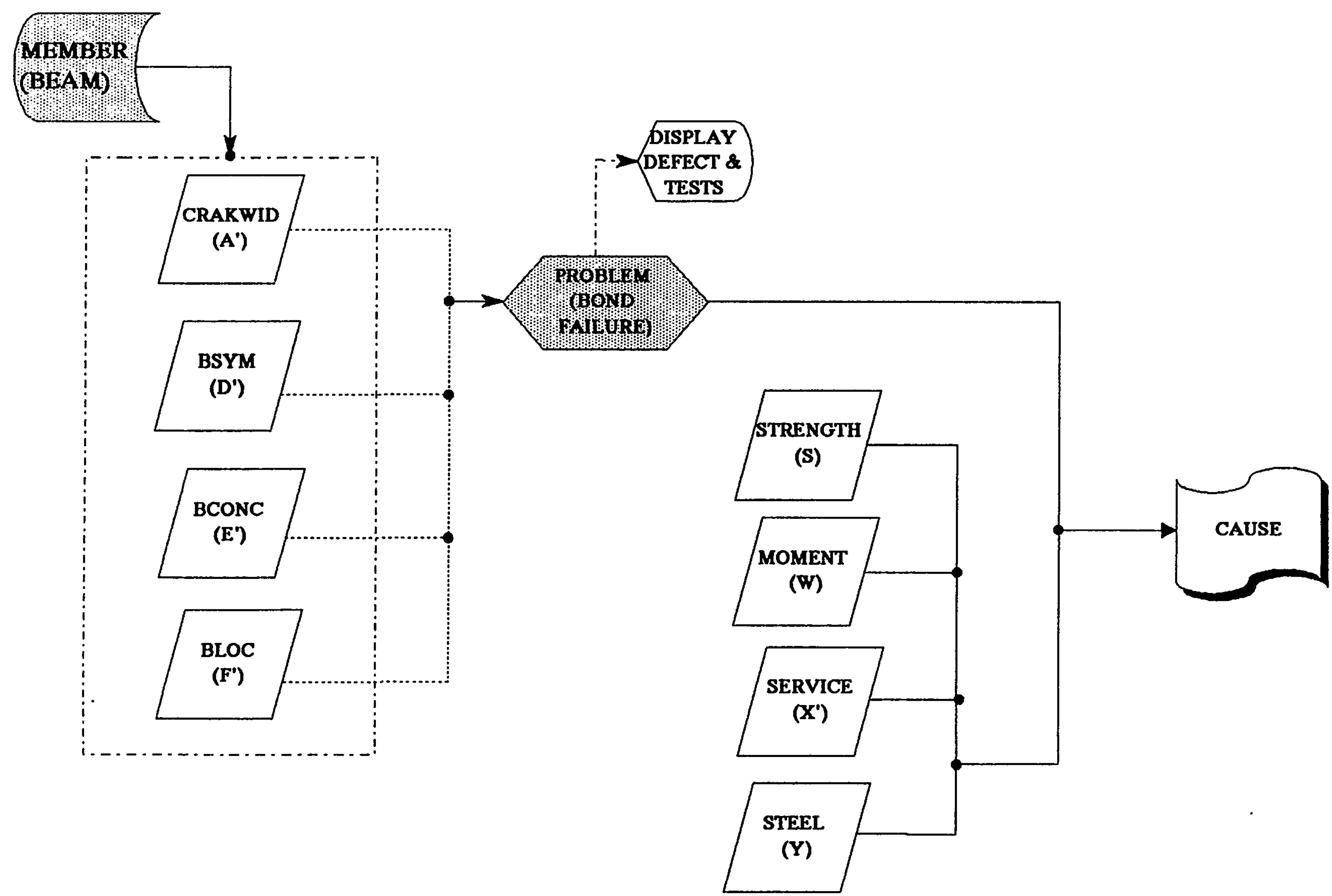


Fig 5.17 Decision Tree for Bond Failure in Beams

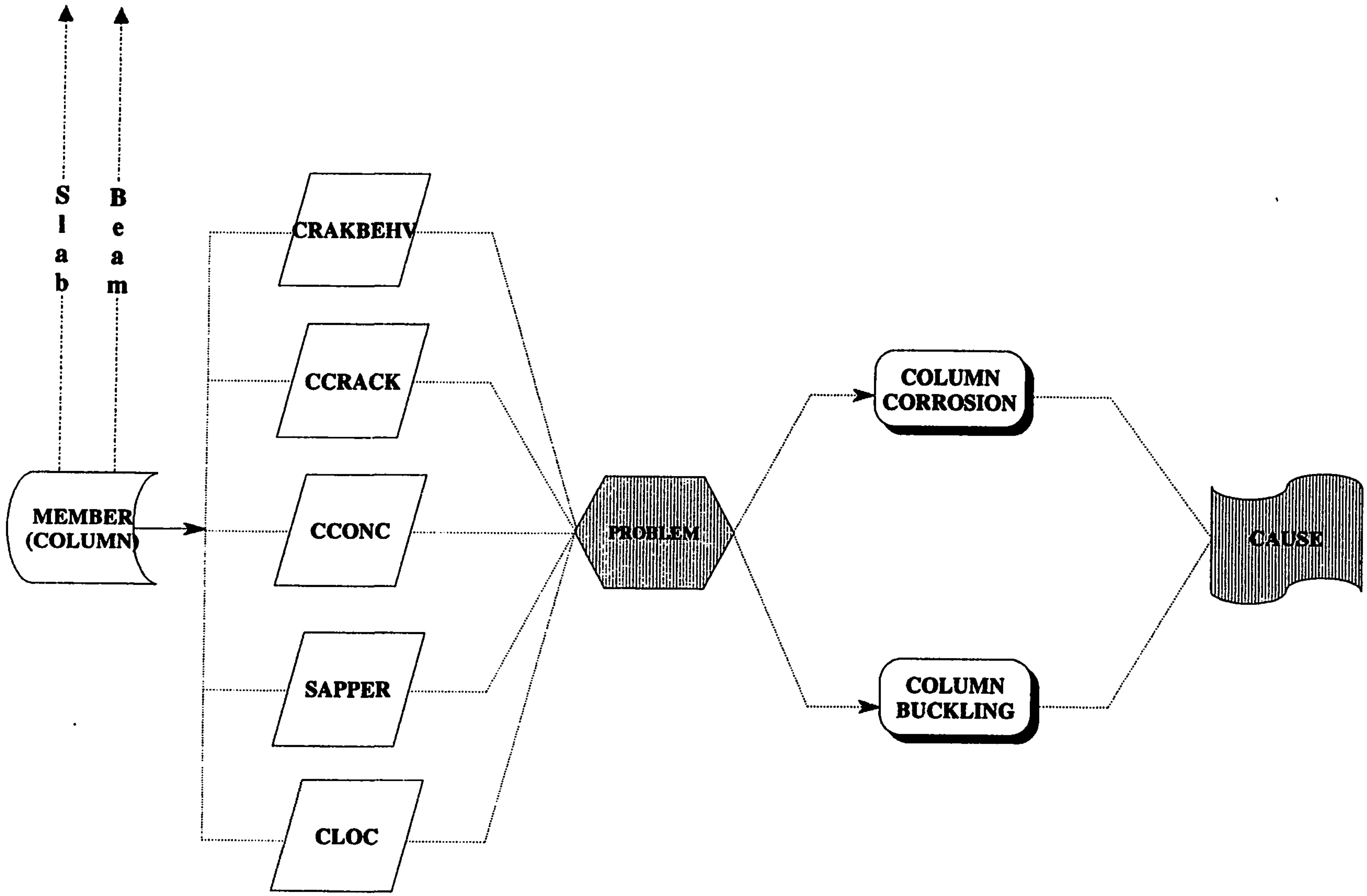


Fig 5.18 General decision tree for search root through columns

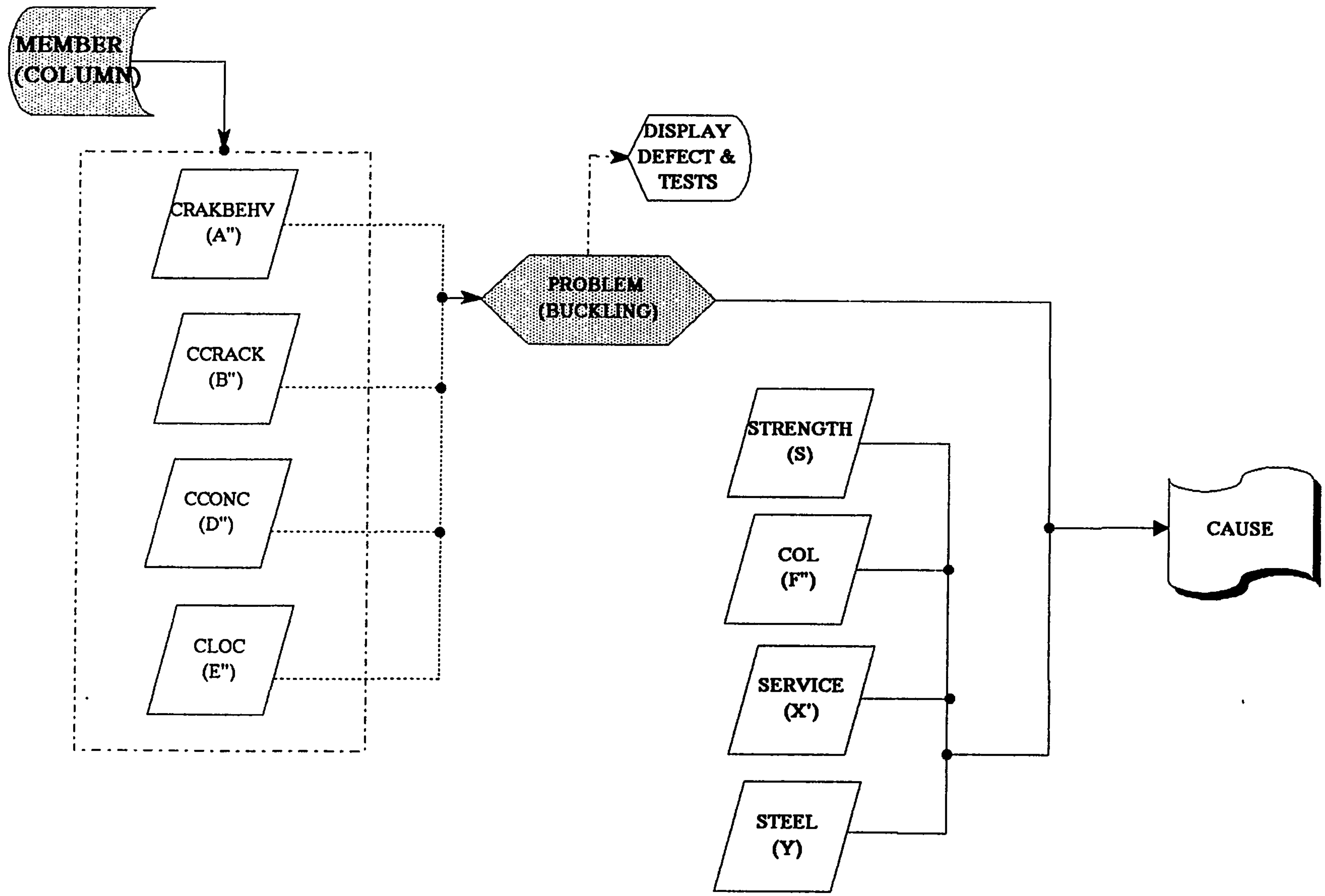


Fig 5.19 Decision Tree for Buckling in Columns

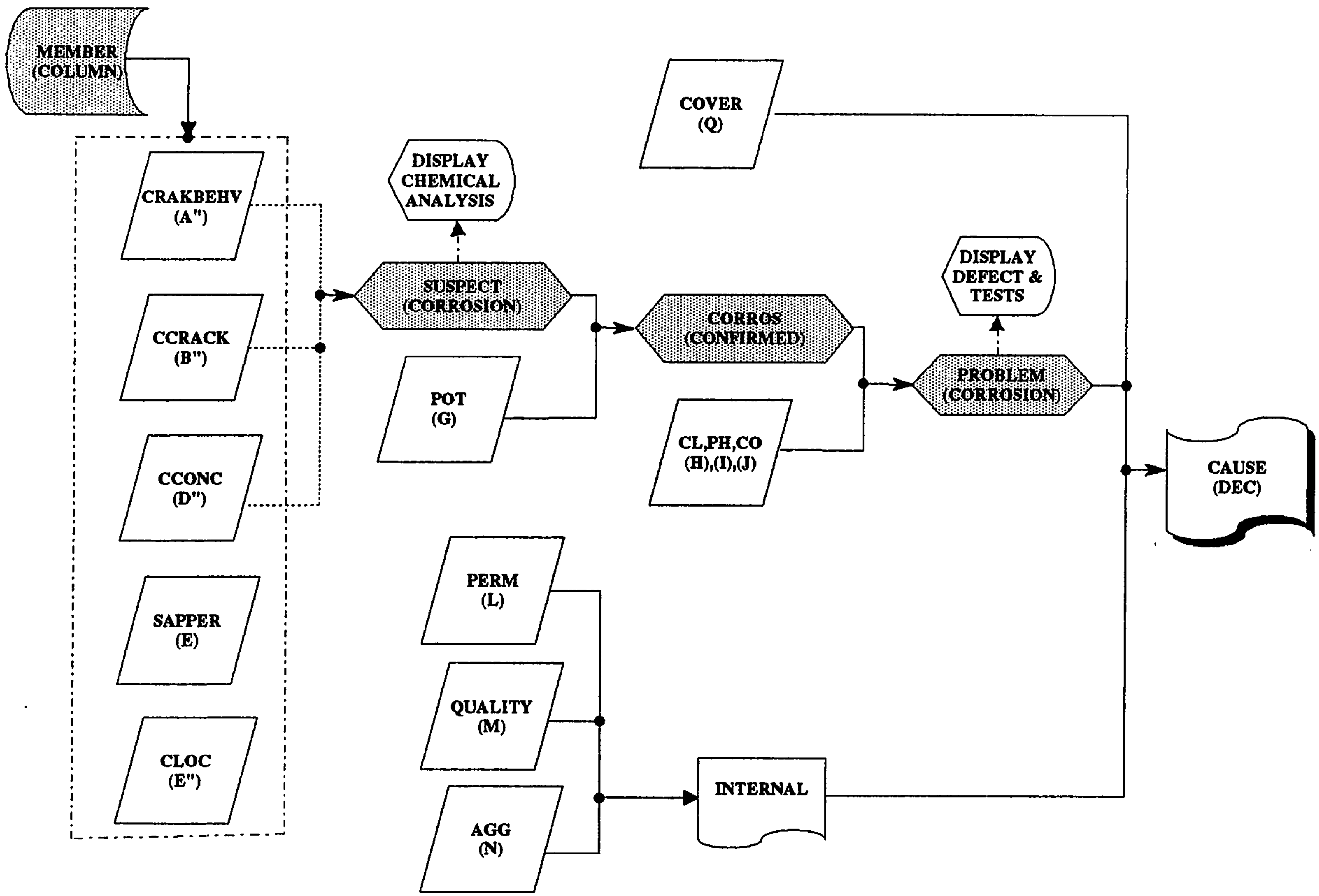


Fig 5.20 Decision tree for corrosion in columns

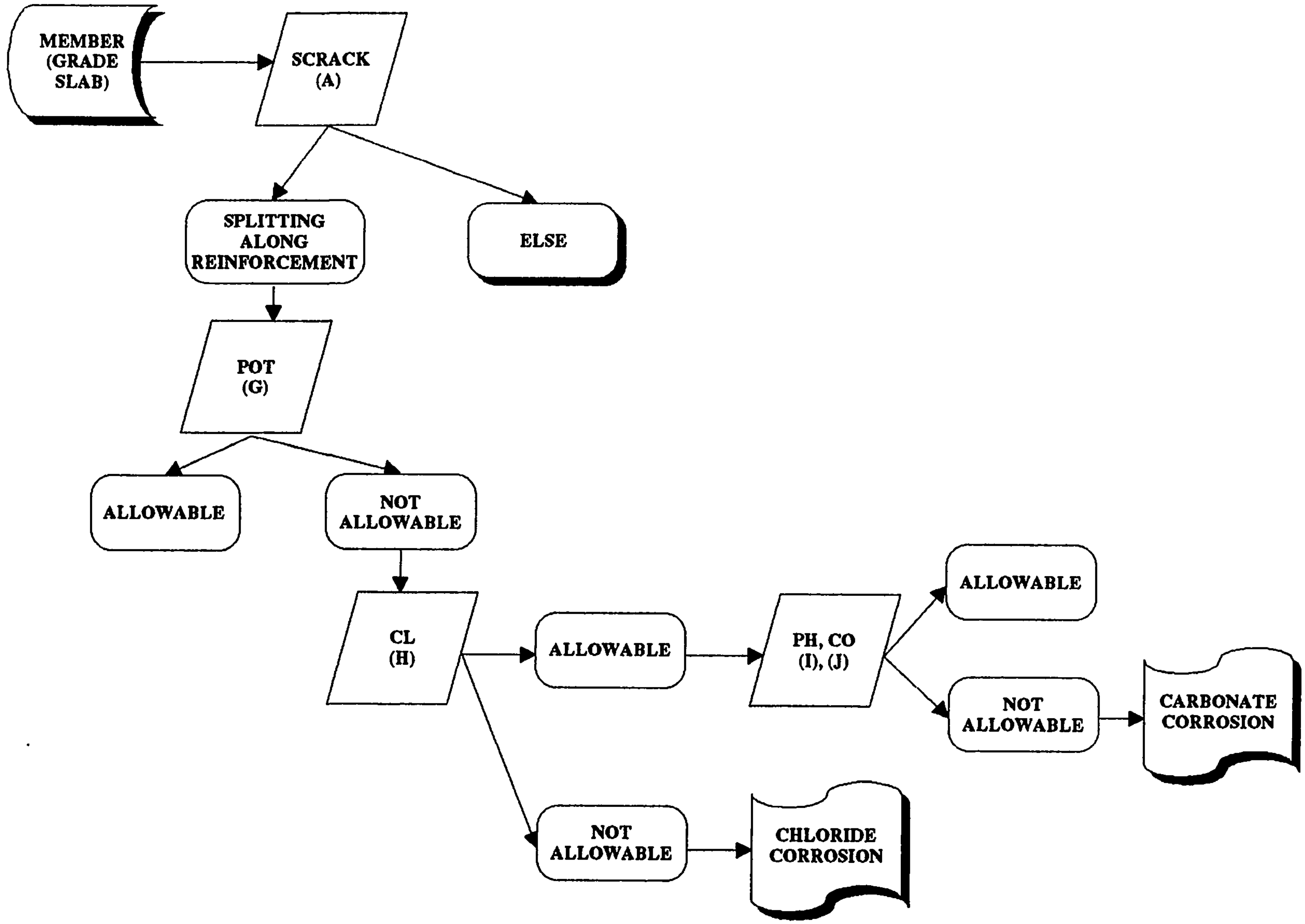


Fig 5.21 Detailed decision tree for corrosion in grade slabs

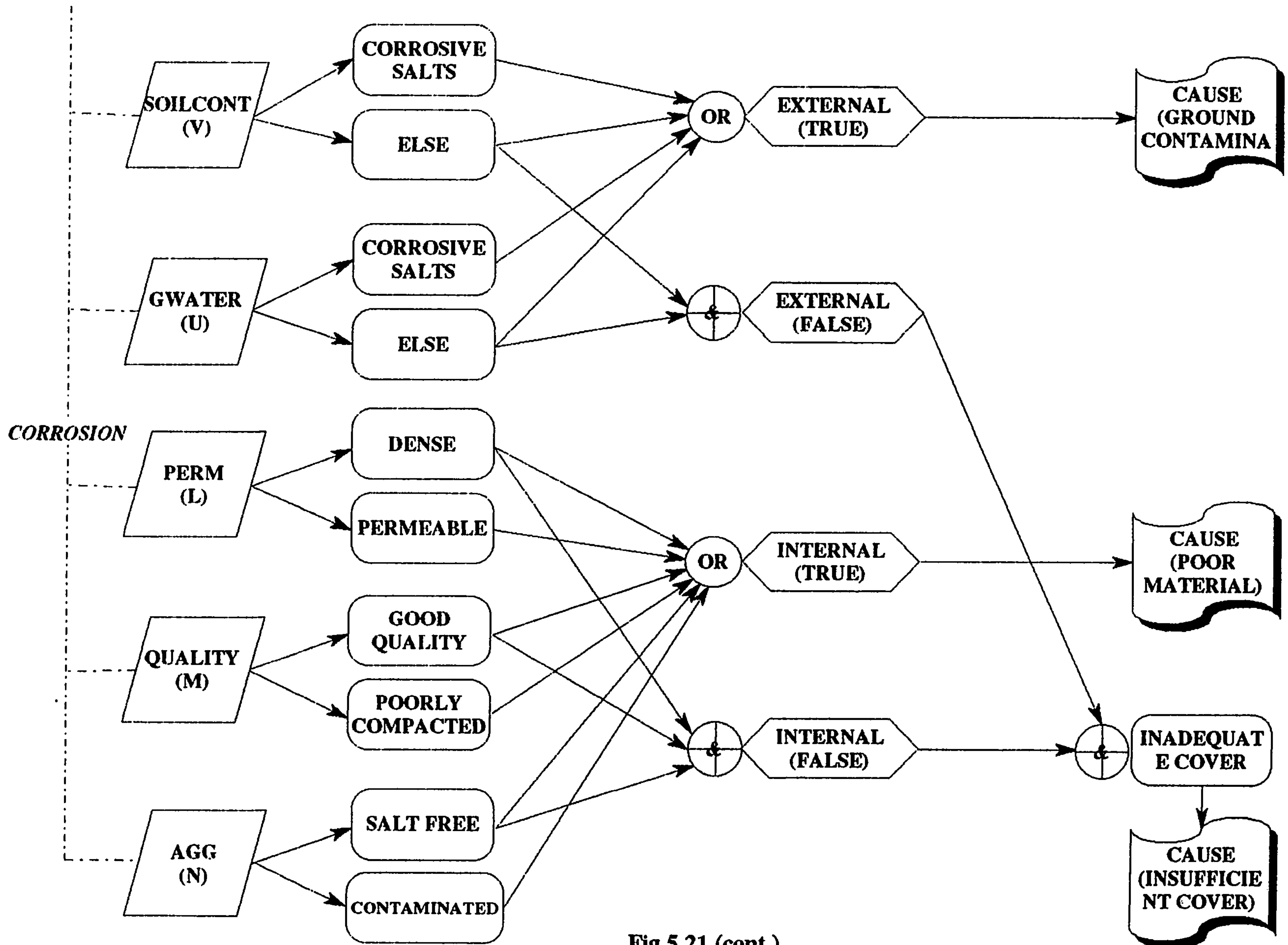

CORROSION
SOILCONT
(V)
GWATER
(U)
PERM
(L)
QUALITY
(M)
AGG
(N)
CORROSIVE SALTS
ELSE
CORROSIVE SALTS
ELSE
DENSE
PERMEABLE
GOOD QUALITY
POORLY COMPACTED
SALT FREE
CONTAMINATED
OR
&
OR
&
EXTERNAL (TRUE)
EXTERNAL (FALSE)
INTERNAL (TRUE)
INTERNAL (FALSE)
CAUSE (GROUND CONTAMINA
CAUSE (POOR MATERIAL)
&
INADEQUAT E COVER
CAUSE (INSUFFICIE NT COVER)

Fig 5.21 (cont.)

5.3 Evolution of Rules

The relationships established previously are implemented or associated together in the form of production rules. The production of rules starts with variables determine other known variables when inferencing starts, i.e., bottom level variables. Then we proceed with the next concept and continue in a similar fashion until each concept is represented in the form of a rule. The process proceeds until all interrelated variables affecting the decision path in a decision tree are implemented into rules.

We will illustrate the building of rules on a specific example defect case; same as before, (corrosion of slab on grade). The system asks first about the defected member and analyzes the symptoms, which lead to decide on the suspicion of occurrence of corrosion. To perform this work, rule *S411* is created. It asks in its premise for the values of the variables *MEMBER* and any of the values of the variables *SCRACK*, *SAPPER*, or *SCONC*. Satisfying the premise of this rule, fires the rule and assigns a value for the dummy variable *SUSPECT*. Rule *S420* uses the value of *SUSPECT* plus quarrying the value of *POT* to evaluate the dummy variable *CORROS*. Afterwards, several variables need to be tested ,i.e., *CL*, *PH* and *CO*, along with the satisfied variable CORROS in order to assign a value for the sub-goal variable *PROBLEM*. The induced rules for this purpose are *S421* and *S422*.

At this level a sub-goal variable *PROBLEM* is known and its value takes over to direct the search to fulfill the diagnostic task. To set a value for the goal variable *CAUSE*, it needs the values of two dummy variables *INTERNAL* and *EXTERNAL*, beside the known variable *PROBLEM*. This is achieved in rules *S427* to *S430*. Yet, *INTERNAL* and *EXTERNAL* still are not tested. Concerning *INTERNAL*, three variables contribute to its evaluation. These variables are *PERM*, *QUALITY*, and *AGG*. The relationship is drawn into rules *S423* and *S426*. The variable *EXTERNAL*, as well, needs two variables *GWATER* and *SOILCONT* to be questioned. For this purpose, rules *S424* and *S425* are built to simulate the relationship.

Special case occurs if both of *EXTERNAL* and *INTERNAL* evaluate to false. To handle such a case, the variable *COVER* needs to be checked to decide on the goal *CAUSE*. The relationship is satisfied in rule *S431*.

This process is repeated to include all interrelations between variables and any possible logical decision path through which a realistic attribute may add or enhance the diagnosis process. Appendix-E includes the complete listing of the induced rules.

5.4 Structure of the System

CONCEXS's knowledge base is stored in three different interrelated sub-rule bases, each of which is called a rule set. The three existing rule sets are:

1. The *Slab* rule set; it includes all rules that perform the diagnosis of a deteriorated slab or slab on grade. It includes as well, escape rules that consult the other rule sets in case their service is required. Moreover, this rule set includes the general environment control of the expert system, such that the initial and final statements which constitute the global call up menus. These menus initialize the search process and direct the consultation into a specific rule set. Additionally, final statements which display the last portion of the consultation reporting the results, are embedded within this rule set.
2. The *Beam* rule set; it contains the rules addressing the diagnosis of defects encountered in beams.
3. The *Column* rule set; it summarizes the rules which belong to problems in concrete columns.

The system is built in a manner to simulate the same procedures a domain expert may follow to interpret the diagnosis task. Fig 5.22 represents this sequential structure. The structure depends on the interaction between the system and the user during a consultation session. First, the system displays an initial menu that familiarizes the user with how to handle the system and what he should expect from it. Then, another menu appears to let the user select the member of the structure on which the deterioration manifestation is noticed. Now the system starts to develop quarrying windows which ask the user to report the symptoms of deterioration. When the system infers these input values, it evaluates its generic rules and decides on the problem which mostly manifest in the

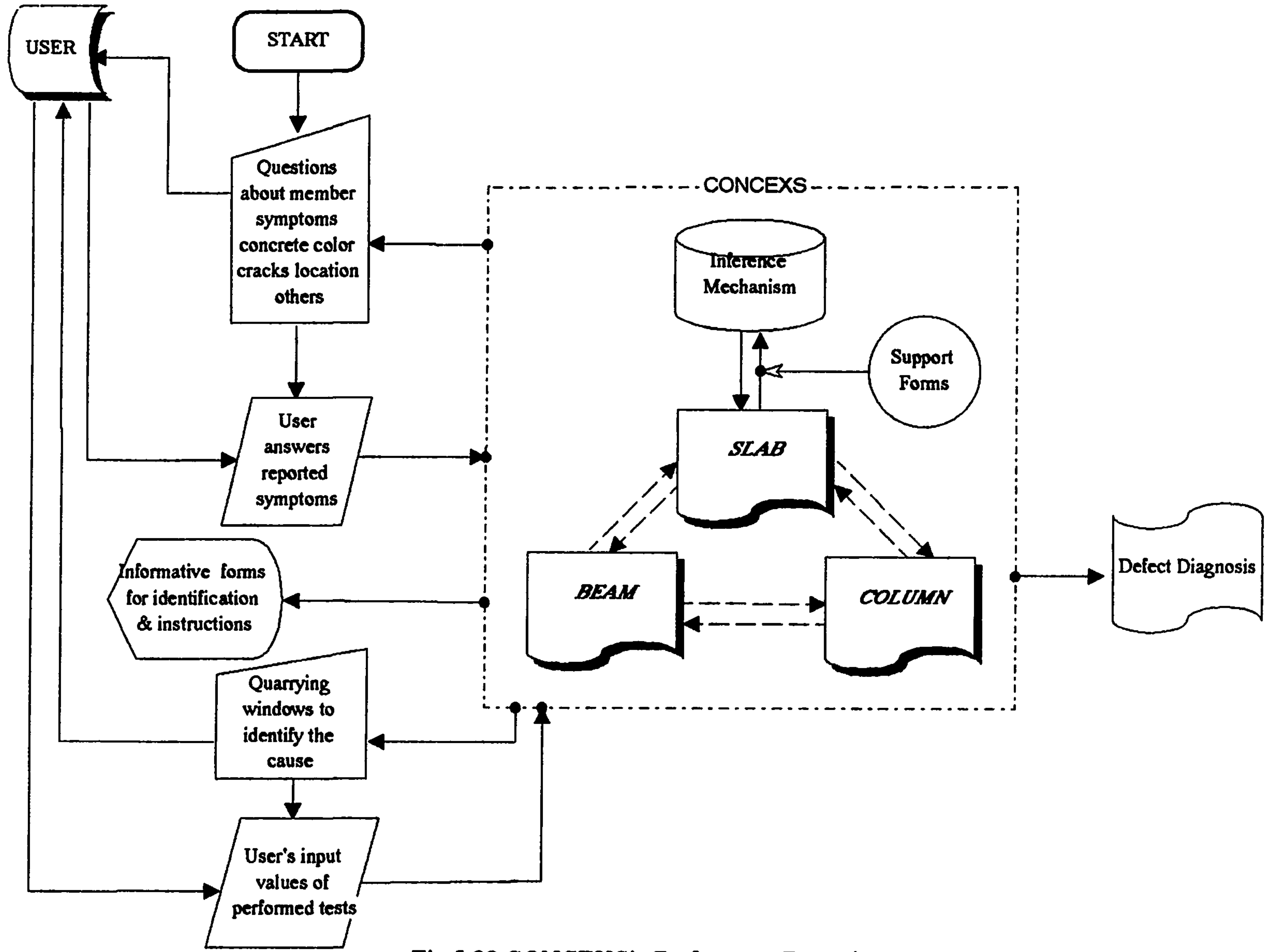


Fig 5.22 CONCEXS's Perfrmance Procedures

way presently encountered. This problem is displayed to the user along with a list developed from the built-in knowledge base to teach the user what suitable test procedures he should follow to diagnose the agent that resulted in the defect.

Afterwards, *CONCEXS* furnishes several quarrying menus to accept the values input by the user. As the user inputs the findings of the performed tests, the system analyzes these values and think upon the value that satisfies the goal variable. Eventually, the output of the consultation is the cause which the system -based on its stored knowledge- finds to be the most suspected contributing factor.

5.5 Features

An extremely important benefit of using -the building shell- *GURU*, is its unique versatility in building rule sets. This facilitated a significant reduction in the number of rules needed to capture the expertise of the diagnosis problem domain. As a result, this means faster inference as well as easier rule management.

CONCEXS at present, manipulates 16 dependent cases in slabs, beams, and columns. In order to perform the diagnosis task, it utilizes 42 variables along with their values. The system produces 47 different decisions representing the result of the diagnosis procedures. This data manipulation is handled in 110 production rules.

A powerful feature the system exhibits is its generic call up menus which act as informative screens to teach the user the required tests to be performed. As well, they prepare him for the data entry, he is expected to input. The system is geared with a list of these forms that are called upon several times during a session whenever needed.

An additional feature, that is facilitated by GURU, is the help screens that appear whenever requested. In case a user is in doubt why a piece of information is needed, or how a certain decision is reached, he may press a key, and a (why window) appears stating lines of helpful information. The information loaded into these windows were carefully stated into each concerned rule to provide a satisfactory answer to the users quest.

Furthermore, line of reasoning option in the GURU environment, provides a very important tool for the user in case he wants a comprehensive data sheet of the summary of a consultation and how a decision or even the goal is achieved. This facility depicts a list of all the fired rules, the utilized variables, and their assigned values.

The system knowledge base is generalized to a certain extent to facilitate future expansions and additional performance enhancement. This feature is noticed in both the developed variables and the assignment of values. Concerning the variables, they are generalized to the degree needed to satisfy the objective of this study. If a more thorough diagnosis is needed emphasizing the role of certain more detailed attributes, the general variables can be easily split and replaced by more detailed variables in the same place in their addressed rules. Concerning the values, some additional values are not used at present -they are marked-, which are intentionally left for future expansion. Moreover, if a specific group of values is needed, it can easily be inserted in place of the old values.

CHAPTER 6

CASE SIMULATION

This chapter will illustrate example runs of the developed knowledge base expert system. It will depict a detailed description of an example consultation session. To achieve this aim, two concrete deterioration case studies are selected. These cases are, corrosion of columns and settlement of slabs. The cases were selected among several other cases that were utilized for *CONCEXS'* development. They are obtained from consultant experts in Saudi Arabia, for real life problems that occurred in the region.

First, each case is going to be illustrated as done in normal practice. Each case summarizes how expert perceived and interpreted the apparent symptoms. Details of performed surveys and investigation of the structures that manifested these cases are highlighted. As well, the findings of the tests and their contribution to cause diagnosis are listed.

Then, each case is going to be manipulated through *CONCEXS* to see its interpretation. Step by step tour through a sample consultation is presented. The reason is to compare and evaluate *CONCEXS'* performance against normal practice, and find out if it draws the same decisions as done by diagnostic human experts.

6.1 Slab Settlement Case

The case occurred at some residential buildings in Al-Jubail city, Eastern of Saudi Arabia. Cracking and deterioration of reinforced concrete slabs in the buildings was observed. A professional engineering consultant office has been assigned to conduct a study to determine the causes, extent, effects, and methods of repair for rehabilitation of the structure.

6.1.1 Case Attributes

Upon visual inspection, visible structural cracks have been detected in the slabs of the structure. Major cracks were observed along the outer edges of the slab at a distance from the reinforced concrete walls. The cracks have a distinguished pattern of mainly existing close and parallel to the supporting walls, Fig 6.1. There were no signs of any rust spots, efflorescence or any chemical salt deposits on the delaminated areas or around the cracks. Moreover, it is obvious that the slab's top surface has some non-uniformity in elevation, particularly the affected areas.

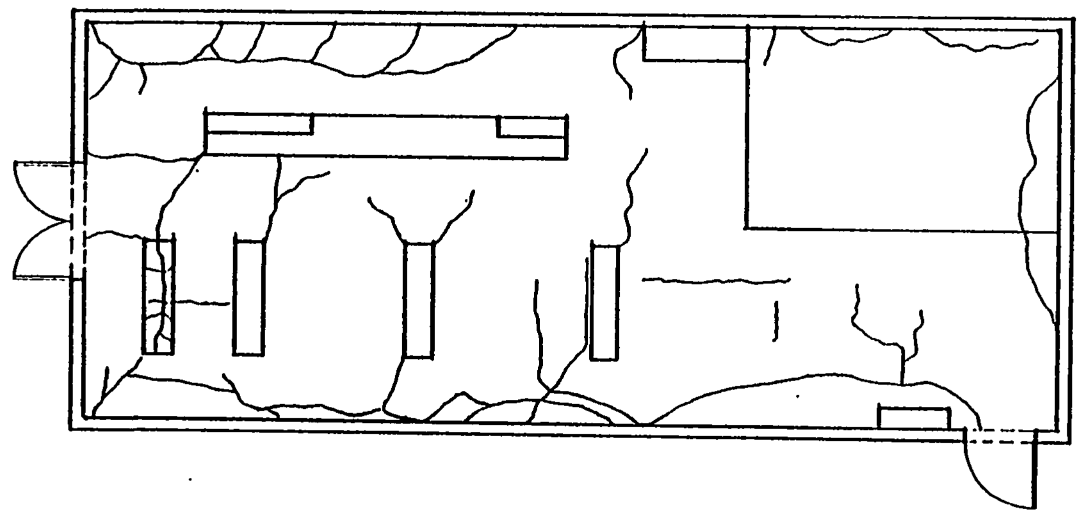


Fig 6.1 Major Settlement Cracks Manifestation in a Residential Building.
(McClelland- Suhaimi, 1990)

The study of "As-built" drawing together with the review of structural analysis showed that the existing structure is sensitive to any differential settlements, due to the rigid framing action between the flexible slab and the rigid supporting walls. Also, structural calculations proved that the slab has excessive flexibility, thus stresses generated from ordinary loading can exceed the ultimate strength of the slab and the formation of plastic cracks had been inevitable. The slab sections were found to be unsafe under the considered parameters.

To obtain information concerning the actual physical condition of the concrete slab, a number of field tests were conducted. Test results indicated the following:

- Using covermeter survey, the spacing of reiforcement were measured.
- Concrete sompressive strength is within the oroginal design value.
- Water absorption, voids and destiny of concrete are within the acceptable limits.
- Carbonation is minimal.
- Chloride content exceeds the allowable limits possibly due to high original chloride contents in the concrete. this is a major threat to reinforcement and indicates that corrosion may have already started.
- An unltrasonic survey was conducted and revealed that the concrete is of good quality, except at locations corresponding to the cracks.

Although no signs of corrosion have been evident, yet the presence of cracks shall undoubtedly lessen the rebars protection. As a result, corrosion rate shall be accelerated and raised by the exceptionally high chloride contents in the concrete.

Based on the aforementioned, it has become evident that the existing plastic cracks are settlement/deflection cracks. These cracks were developed upon overstressing that may have resulted in conjunction of possible differential settlement and/or slab deflection. It is apparent that the slab was not designed to resist the additional tension stresses. Therefore, it is concluded that the present plastic cracks were created as excessive tension stresses exceeded the ultimate strength of the slab.

6.1.2 CONCEXS' Consultation

After the case has been interpreted as done usually in common practice, the developed knowledge based expert system is consulted to observe its performance. A typical diagnosis consultation starts with Familiarizing the user with the system then generating an input screen to accept users selection of the member he intends to diagnose as shown in Plates 6.1 (a and b). In this case, the user is expected to input *slab*.

Then, the system generates several quarrying windows to let the user feed the observed manifestation of the defected member, as shown in Plates 6.2 (a,b,c and d). *CONCEXS* develops these windows from within its symptoms variables to satisfy the first level of the diagnostic consultation; namely, defect identification. The interactive procedure is as

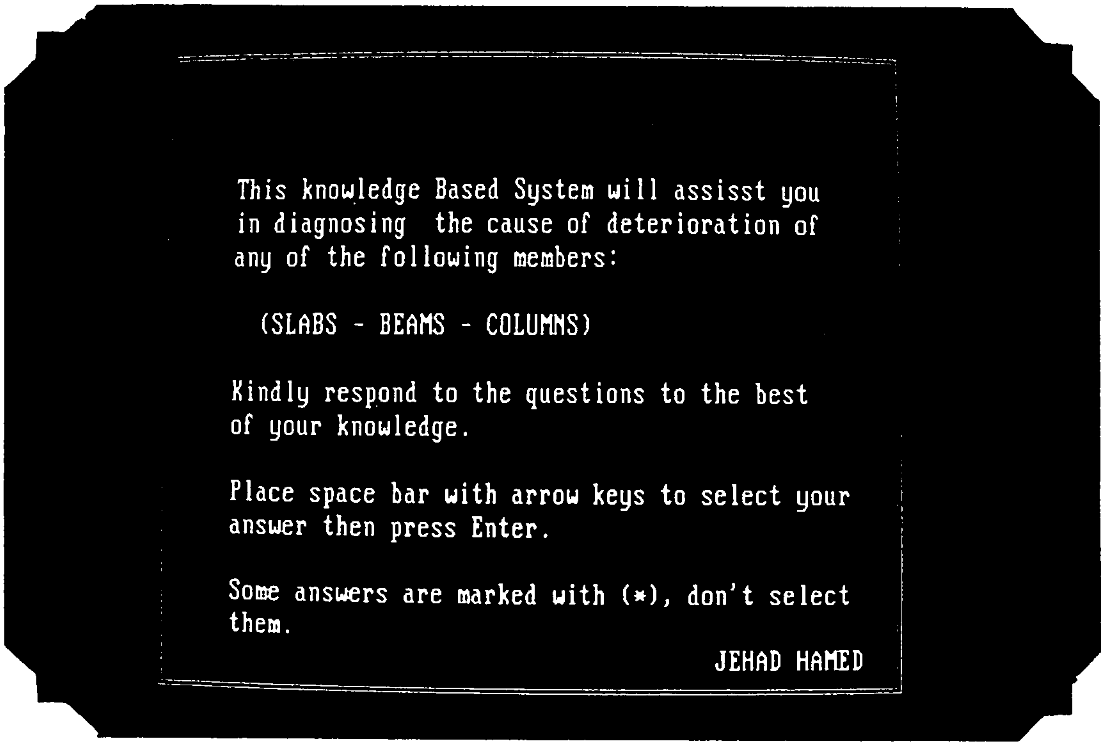


Plate 6.1.a CONCEXS Strarting Screen.

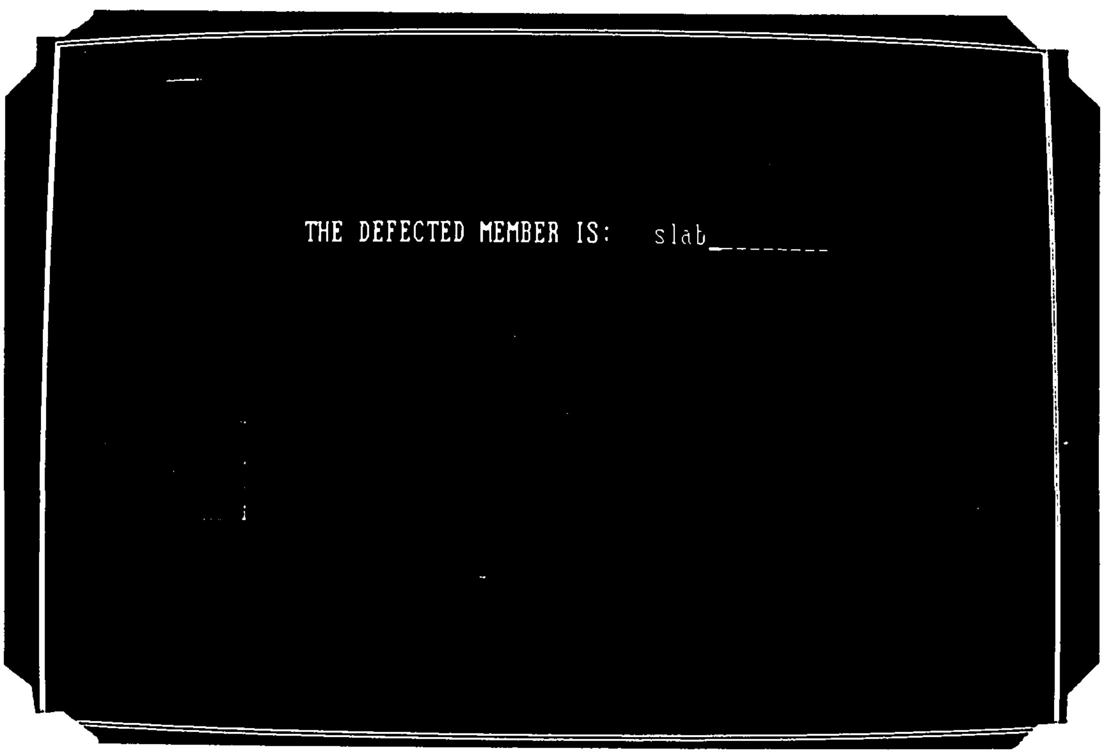


Plate 6.1.b User's Input Scren for Member to be Diagnosed.

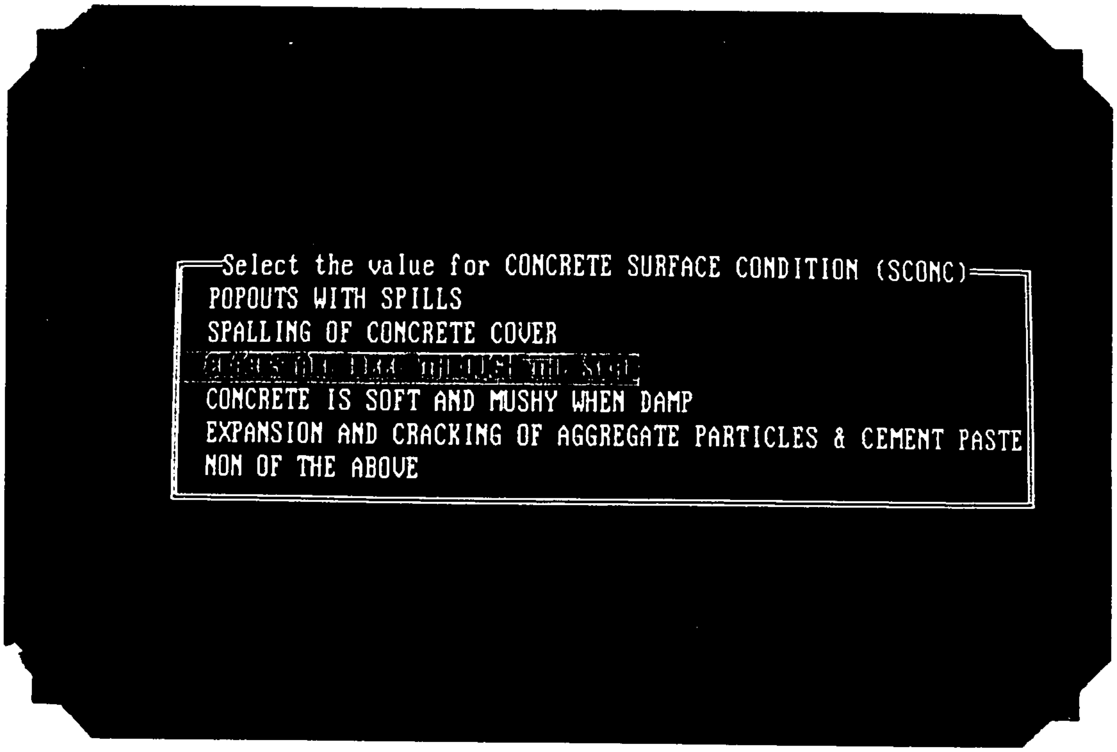


Plate 6.2.a Concrete Slab Surface Condition Variable.

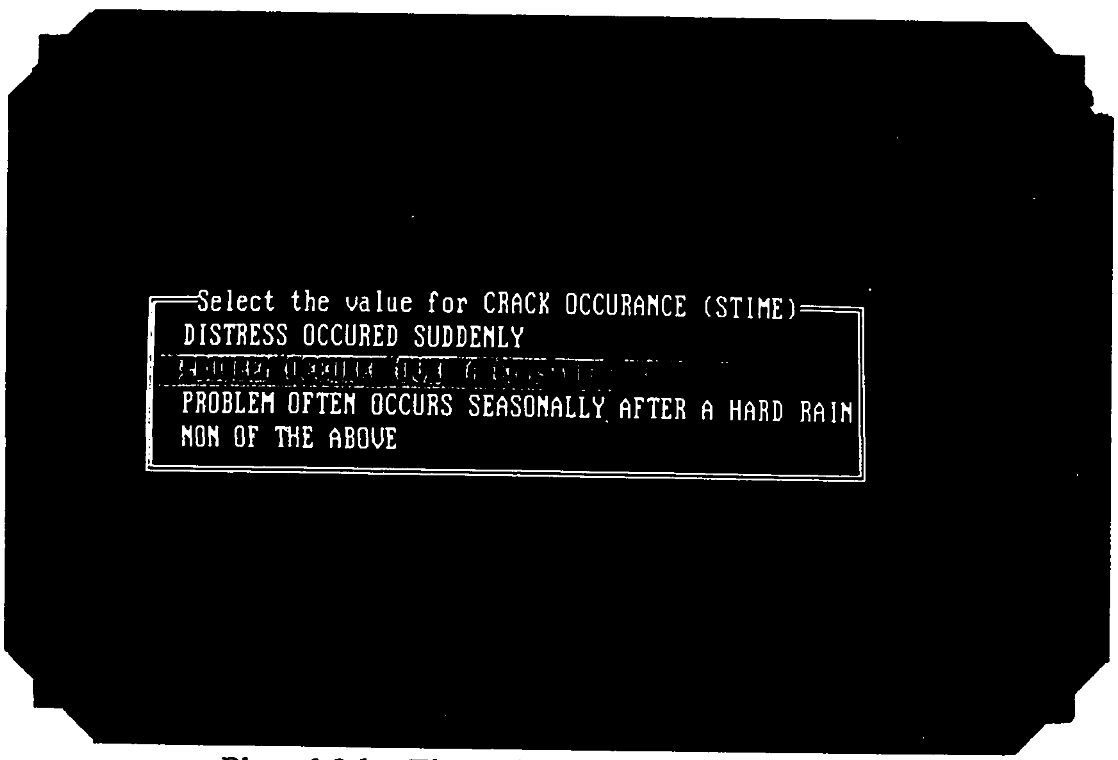


Plate 6.2.b Time of Crack Occurance Variable.

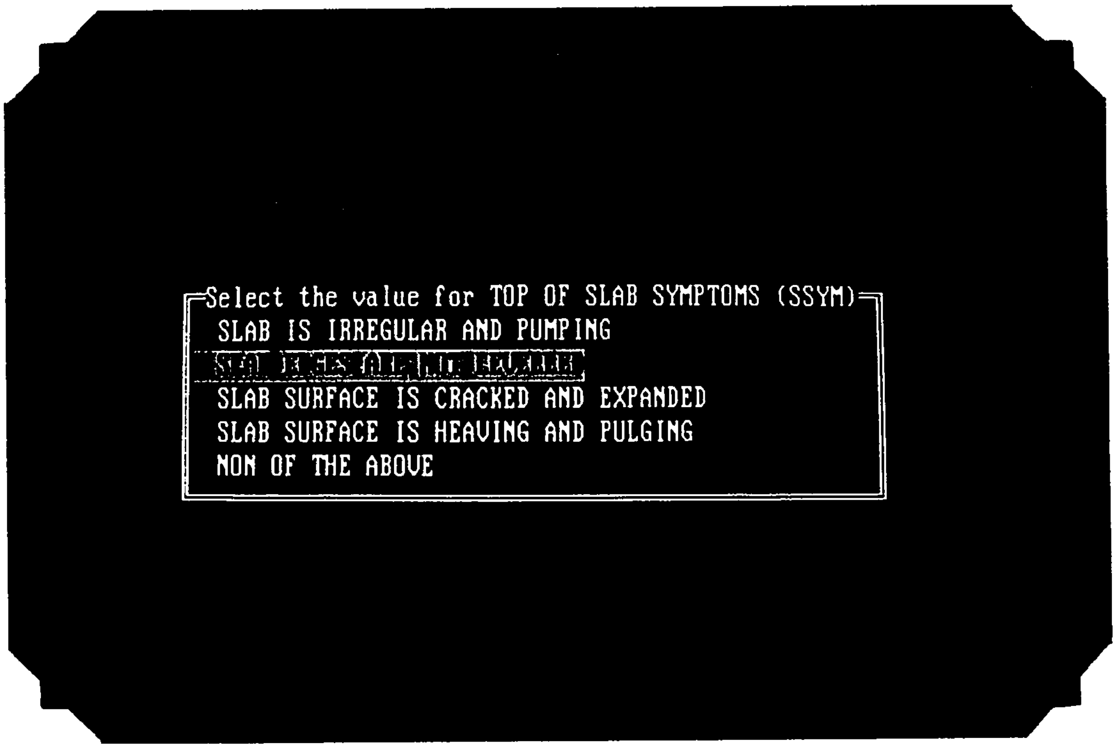


Plate 6.2.c Top of Salb Symptoms Variable.

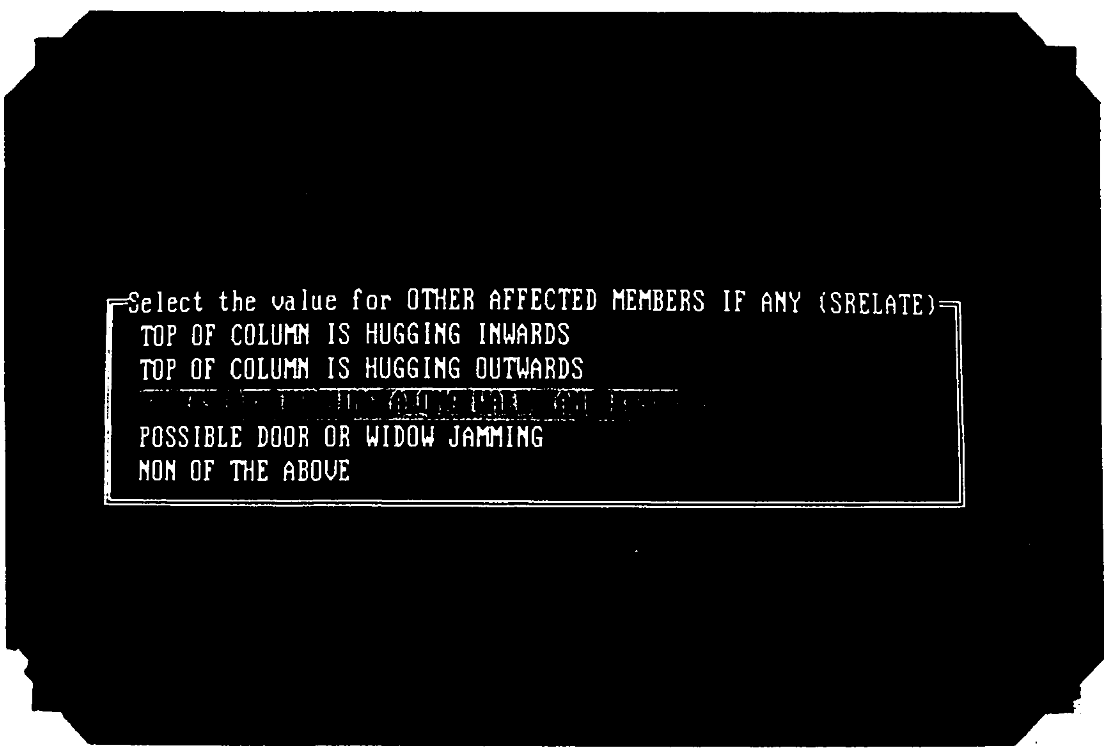


Plate 6.2.d Check for Defect in Other Members Variables.

follows:

- (SCONC) Concrete surface condition in slab is?

  Cracks are deep through the slab.
- (STIME) Time of occurrence is?

  Problem occurred over a considerable time.
- (SSYM) General slab performance is?

  Slab edges are not leveled.
- (SRELATE) Other affected members (if any)?

  Cracks are running along wall, and restrained corners.

The system will use these responses to evaluate the sub-goal variable *PROBLEM*, and assign it a value of "***slab settlement***". This sub-goal is reported to the user in the form of an informative screen displaying the drawn defect. Furthermore, the system now searches through its acquired knowledge and come up with a series of required tests to perform the diagnostic task. These series of tests are reported into a form that is displayed to the user to carry out, to reveal the agent beyond the structural problem. Plates 6.3 (a and b) show the two displayed forms.

Now the diagnostic process is ready to take place. *CONCEXS* searches among its available knowledge concerning the slab settlement problem, and locates the most suspected factors that may cause this problem. For this task, repetitive windows appear to collect the user's findings of the performed tests and investigation. Following these windows, the user selects the values that represent the case under consideration, which will lead to determination of the cause of the defect.

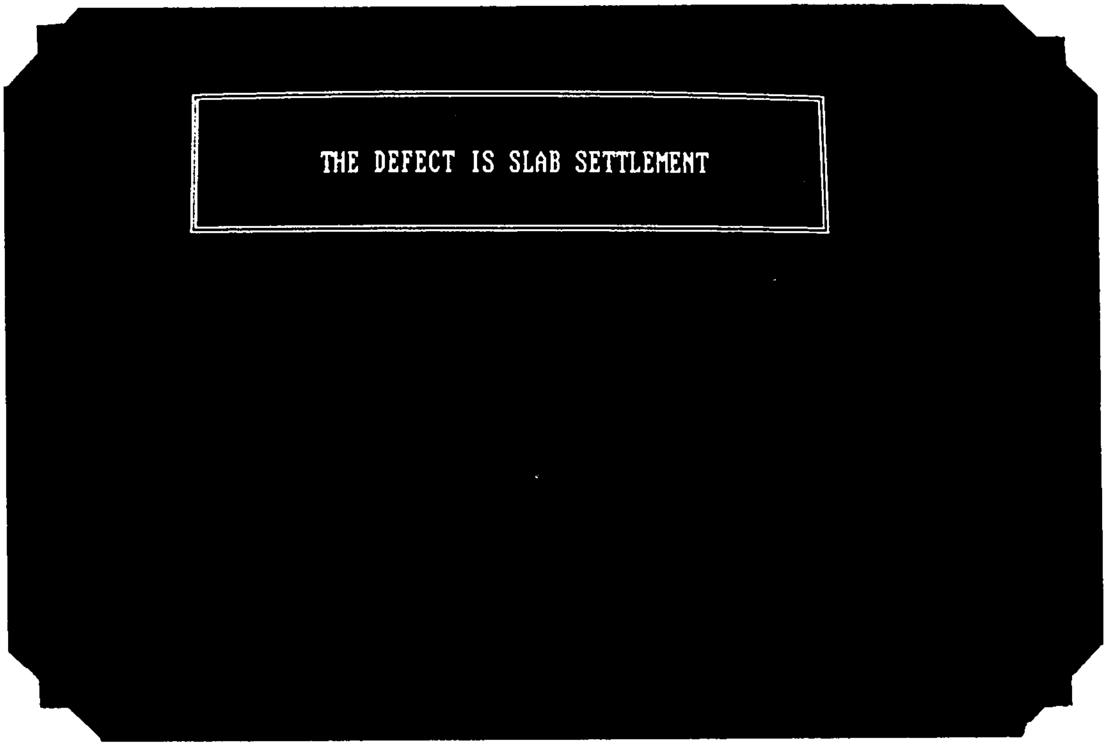


Plate 6.3.a Problem Subgoal is Known as Slab Settlement.

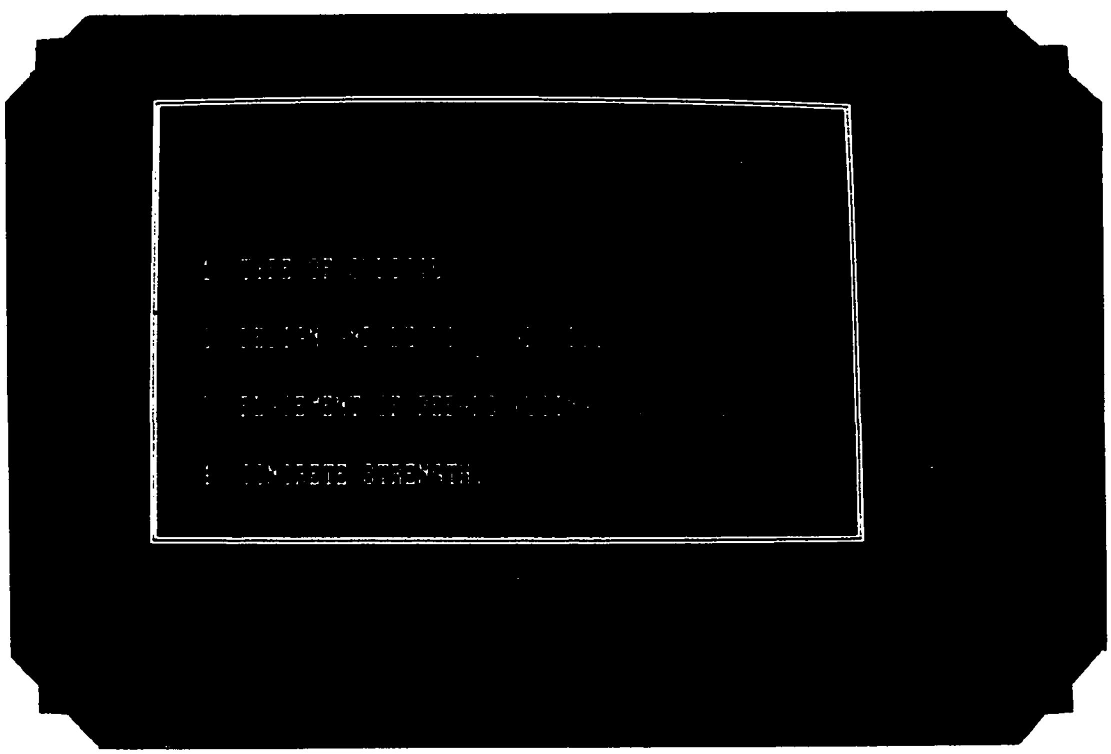


Plate 6.3.b Required Tests to Diagnose the Settlement Case.

Plates 6.4 (a, b, c, d, e and f) illustrate the diagnostic windows. The diagnostic process progresses as follows:

- (STRENGTH) Concrete strength is?

  Concrete strength > specified.
- (SOIL) Soil type is?

  Well confined soil.
- (BEARCAP) Bearing capacity consideration?

  Bearing capacity estimation is safe and adequate.
- (SERVICE) Service conditions?

  Severe deflection under badly designed imposed loading.
- (MOMENT) Bending moment consideration?

  Poor distribution of bending moment.
- (STEEL) Reiforcement provision?

  Bars are poorly placed.

As these values are fed into the system, it evaluates them against its body of knowledge, and detects if they lead into a certain decision. The system checks its vast array of knowledge and relates these input values together, the same way done by human experts to conclude a suitable diagnostic value. The result of this search is compared to the built-in decision values of the goal variable *CAUSE*. If one of the decision values is satisfied, the system selects it and assigns it to *CAUSE*. If a decision value can not be drawn, the system searches again through its production rules. Further quarrying windows may be reproduced, as well, if needed. If the search is unsuccessful, the system assigns an *unknown* value to the

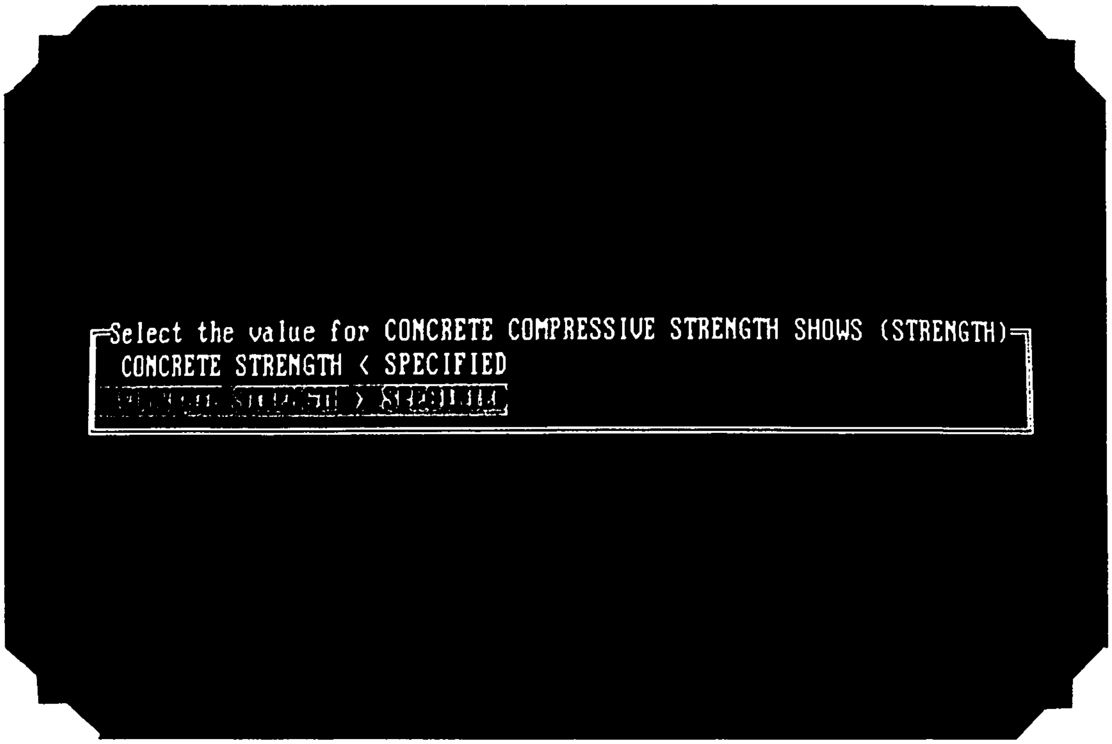


Plate 6.4.a Compressive Strength Check Variable.

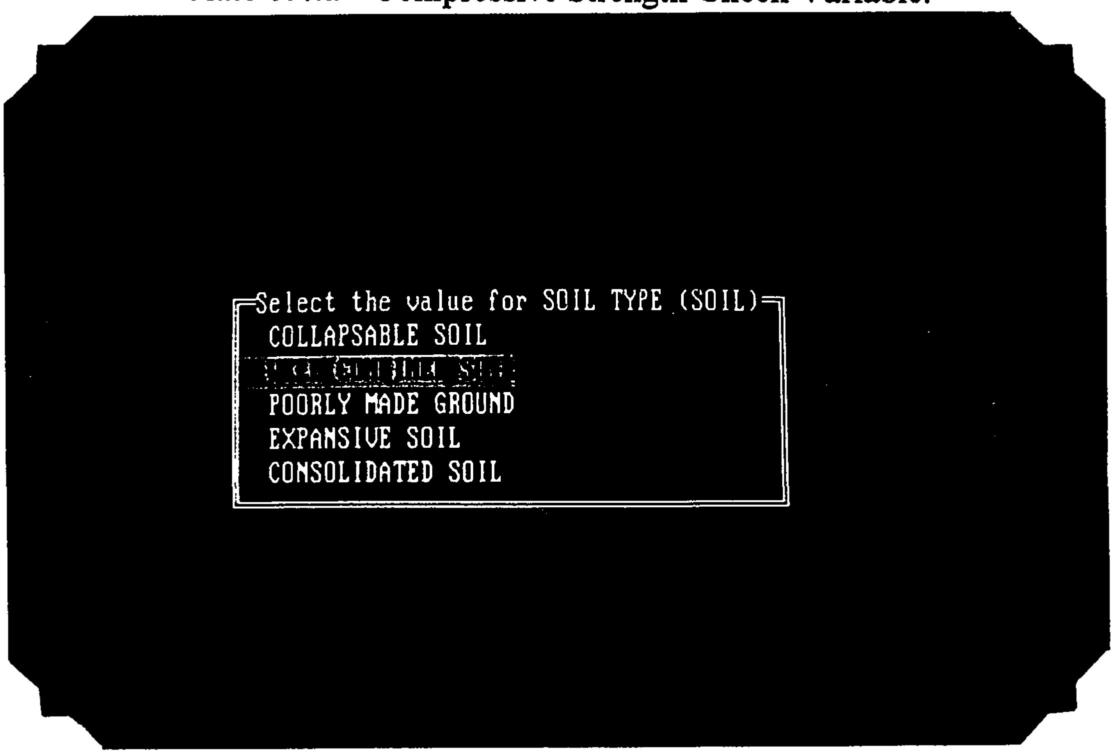


Plate 6.4.b Soil Type Check Variable.

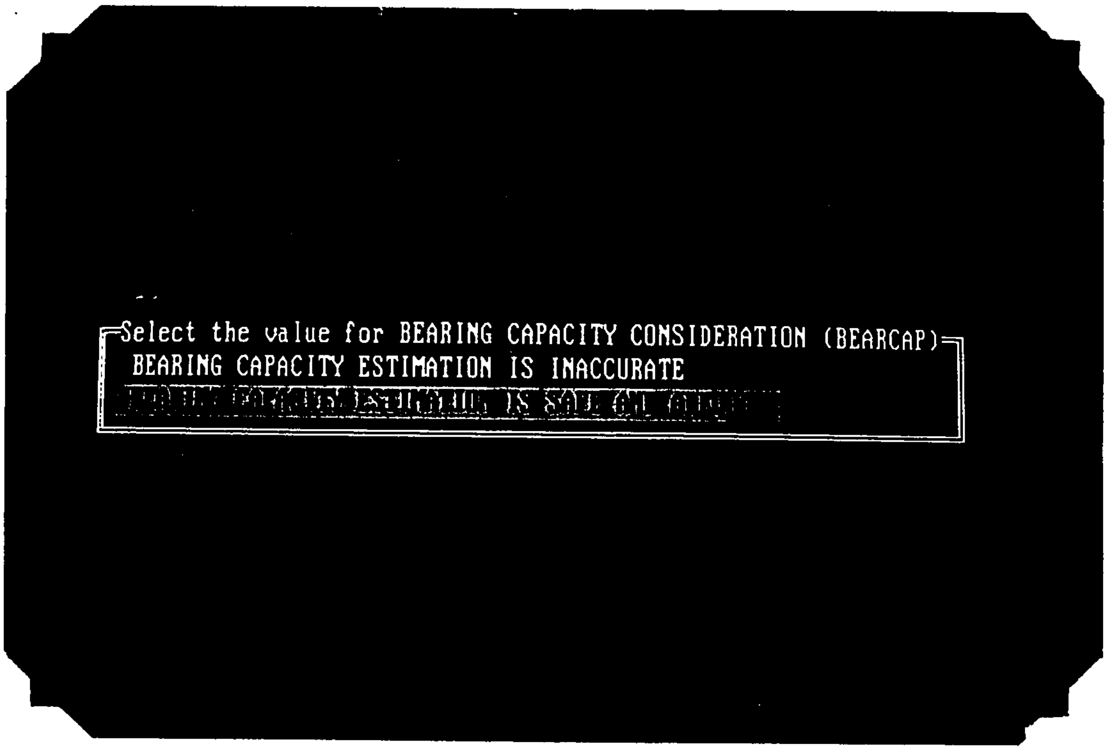


Plate 6.4.c Bearing Capacity Check Variable.

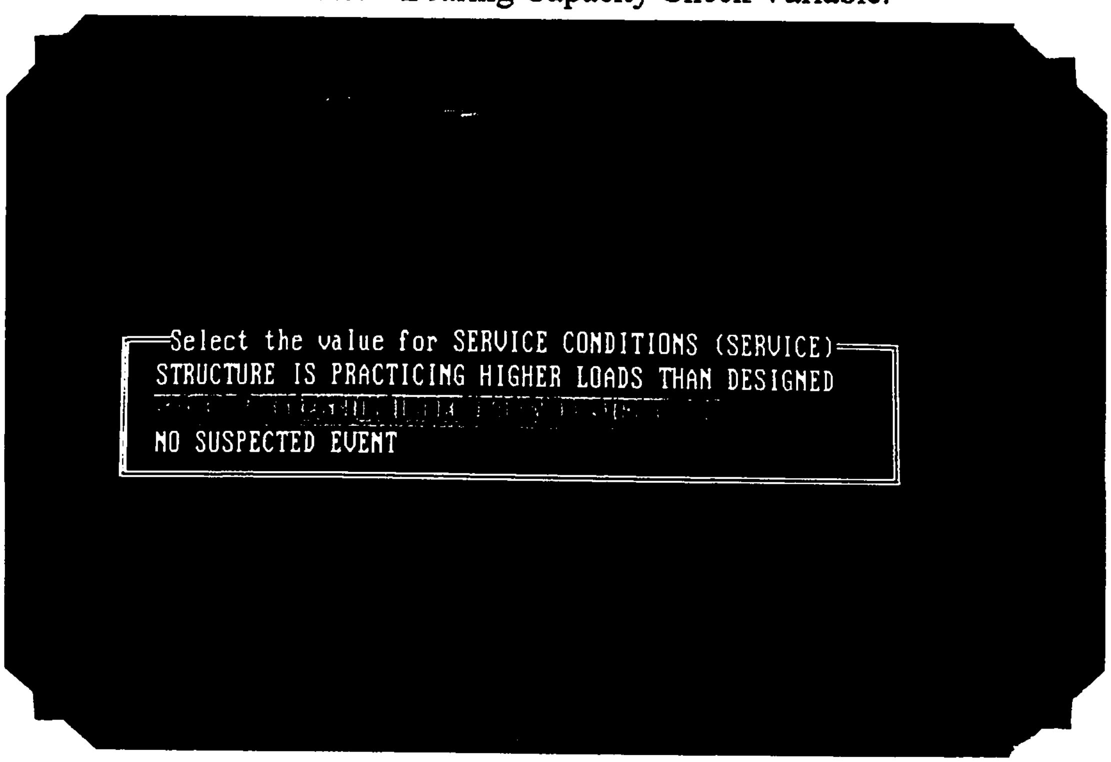


Plate 6.4.d Service Condition Check Variable.

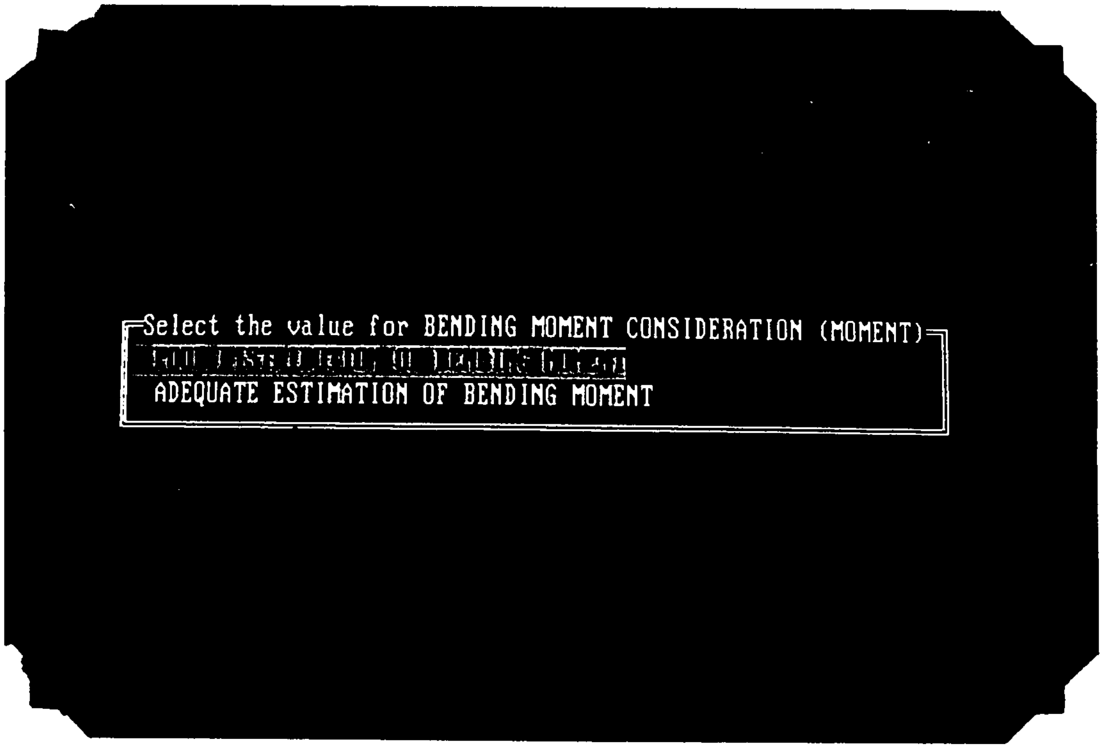


Plate 6.4.e Bending Moment Check Variable.

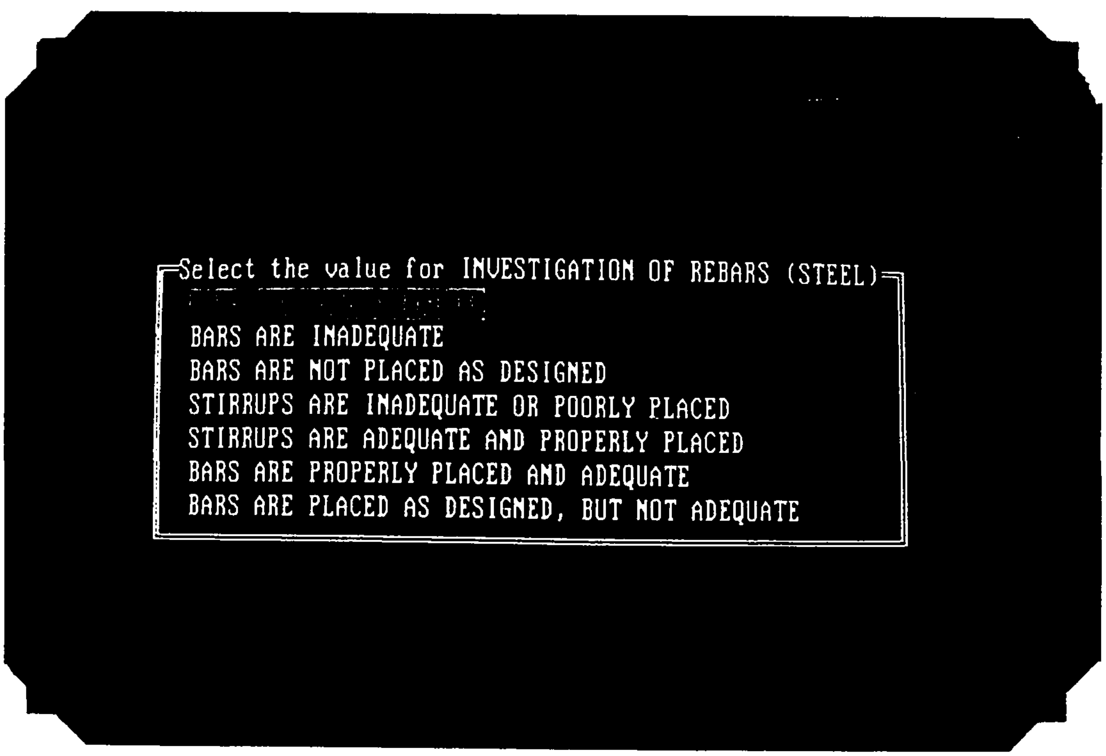


Plate 6.4.f Reinforcement Check Variable.

goal variable, and the consultation may be repeated again. Otherwise, the case is not within the capability of the knowledge of *CONCEXS*.

Diagnostic search for the considered case study is successful. So the system arrives at a decision value that pertains to the intepreted knowledge, as shown in Plate 6.5. The obtained cause is:

Poor reinforcement design or detailing resulting in restrained corners and development of a rigid framing structure sensitive to settlement/deflection delamination.

When a consultation ends, GURU retains a detailed history of that consultation in memory. So a user is capable at the end of any consultation to ask for an explanation of the line or reasoning used during that consultation. This facility furnishes the user with a comprehensive summary of the routes followed to direct the search. It displays a complete list of rules used to derive a decision. Each rule is illustrated along with the values fed by the user. the facility is very beneficial as a concise report of test results, analyzed symptoms, and the drawn decisions.

Another interesting facility is the ability of the system to answer and deliver explanations whenever requested during a consultation. this feature explains how the system arrived at the reported decision and even why it fired a particular rule. The feature is triggered through pressing (control-Y) anytime during a consultation. If invoked, a *Why* window is

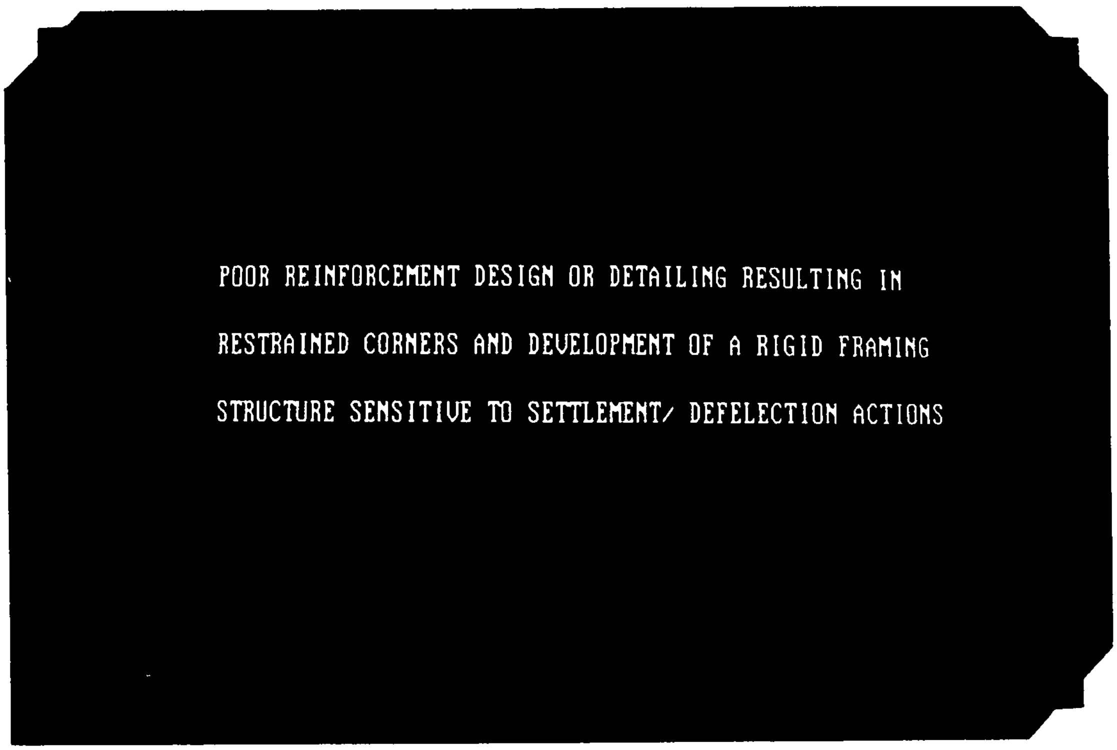


Plate 6.5 The Decision Value for Slab Settlement Case.

displayed. This window delivers an informative information of the reasoning beyond asking for a specific value. The displayed information was loaded to the relevant rules to satisfy various expected questions during a consultation. For example, while the system is asking for the value of the variable *SCONC*, the user may be confused why this value is needed. Then, if he seeks the advise of the *Why* window, a message will be generated to him as follows:

These symptoms are needed to define the type of defect.

This feature is very helpful specially if the system is used for educational purposes for students and engineers, to practice and develop their expertise.

6.2 Column Corrosion Case

This case covers a two floor residential building at Dammam area, Saudi Arabia. When renovation work was commenced on this building, it was found that several structural members were badly deteriorated. Several questions over the structural integrity and stability of the building were raised. Hence, a professional evaluation of the whole structural integrity was called to assess its serviceability. It was intended to determine the extent of deterioration of various reinforced concrete elements of the structure.

6.2.1 Case Attributes

The structure is more than 25 years old. Apparent poor design, detailing and workmanship during construction, poor quality control of concrete and hostile environment have all contributed to the deterioration of the building. This resulted in cracking, delamination, spalling of concrete, and rusting of reinforcement in different structural elements. Many exterior columns show spalling of concrete and the exposed steel is trusted, Plate 6.6. Longitudinal cracks parallel to the main bars are visible in many columns. These symptoms are shared between most members of the structure. Moreover, the cover of reinforcement appear to be low, being generally 10 to 20 mm. In some areas, deflection of slab is significant. Cracks are apparent in areas above the beams, which indicate that the tension reinforcement was not provided or inadequate.

A comprehensive structural investigation was commenced to determine the condition of concrete and the extent of corrosion in the concrete slabs and columns. The field investigation phase of this study consisted of obtaining concrete cores from slabs, beams, and columns. Also, it included performing half-cell potential tests on roof slabs and one column. The executed tests revealed the following:

- Comprehensive strength of concrete is below the required value for similar structures.
- Chloride content in the concrete exceeds the respective allowable limit, specially the exterior side of test speciments.

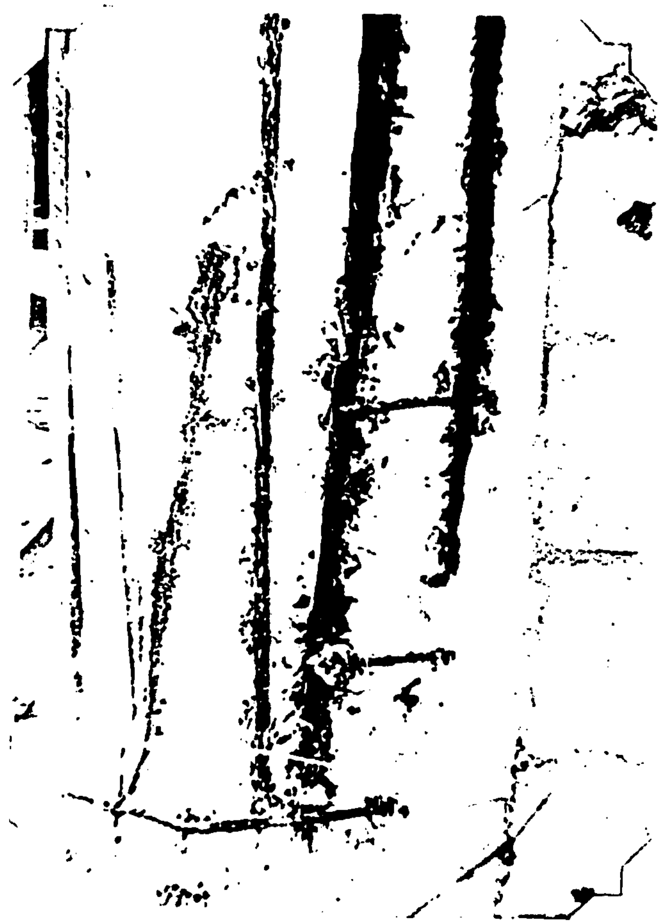


Plate 6.6 Reinforcement Corrosion in Columns.

- Half-cell potential results indicate significant difference within the concrete members.
- Cement content is below required.
- Large number of voids are present in the concrete.
- Water/cement ratio was very high.
- Carboration depth has reached beyond the level of reiforcement.
- The inspection revealed that the design of roof slab is inadequate.
- Excessive deflection is noticed in some slabs.

On the basis of these conclusions, the building was decided to be in a poor structural condition and suffering from severe chemical attack. It was deduced that the following factors stand for the delaminated concrete condition:

- High water/cement ratio and low workable poor quality concrete.
- Low cement content.
- High concrete porosity and low reinforcement cover.
- Concrete cracking due to structural distress.

6.2.2 CONCEXS' Simulation

Again the knowledge based system was consulted to analyze this consideed case. The genral progress of the consultation session is similar to the previous studied case. Attention is directed here to the different considered attributes that affect this chemical attack case.

As most of the deterioration symptoms were observed in columns, the consultation is seeked for a column member, Plate 6.7. The generated quarrying windows for identifying the problem in a column deal with, *CRAKBEHV, CCRACK, CSYM, CCONC,* and *CLOC*. These windows are depicted in Plates 6.8 (a, b, c, d and e). The expected user's responses values flow in the following manner:

- (CRAKBEHV) Behavior of crack in a column?

  Splitting cracks.
- (CCRACK) Crack direction in a column?

  Only vertical cracks.
- (CSYM) Column surface appearance?

  Rust stains.
- (CCONC) Concrete surface condition?

  Spalling of concrete cover.
- (CLOC) Location of defect in a column?

  Any location along reinforcement.

It is *CONCEXS'* role now to infer the input information and assign a value for *PROBLEM*. Yet, the inference procedures encounter several *unknown* variables that still need to be identified. These variables contribute to the decision making strategy to derive a value that satisfies the analysis of a "chemical attack" in the subject member. Consequently, the system initiates a suspected opinion about the occurence of corrosion, and triggers a set of variables to ascertain this suspicion. the system first informs the user of what he is expected to do through generating a list

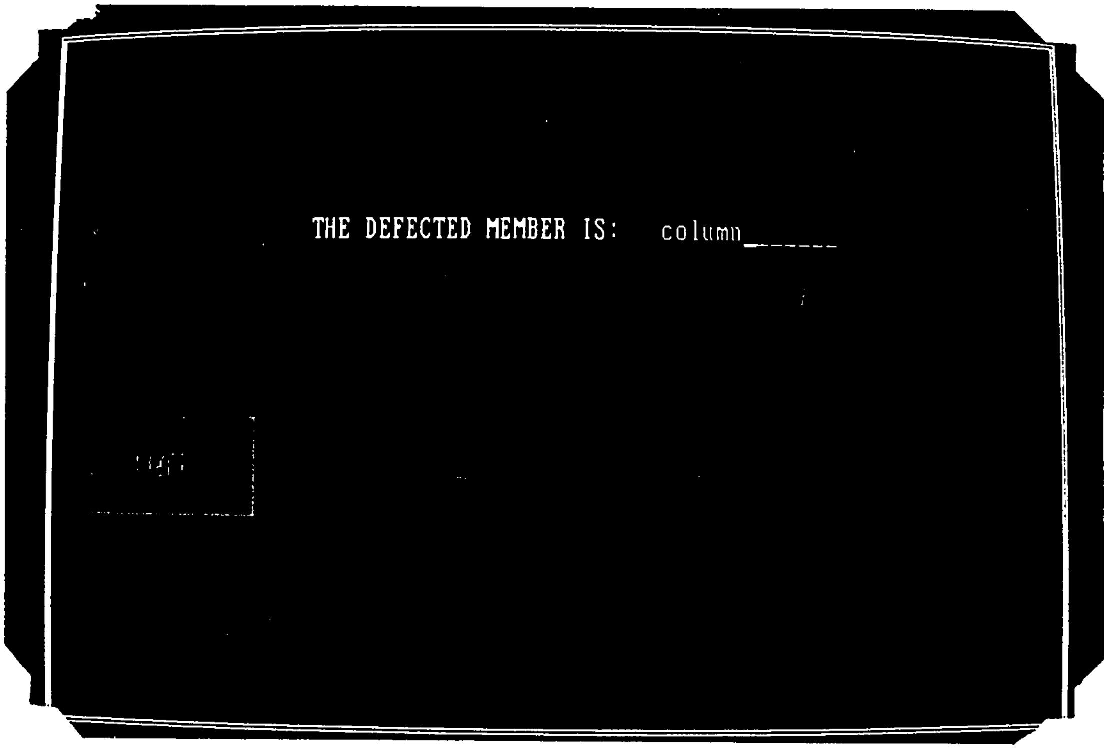


Plate 6.7 User's Input Screen for Column Corrosion Case.

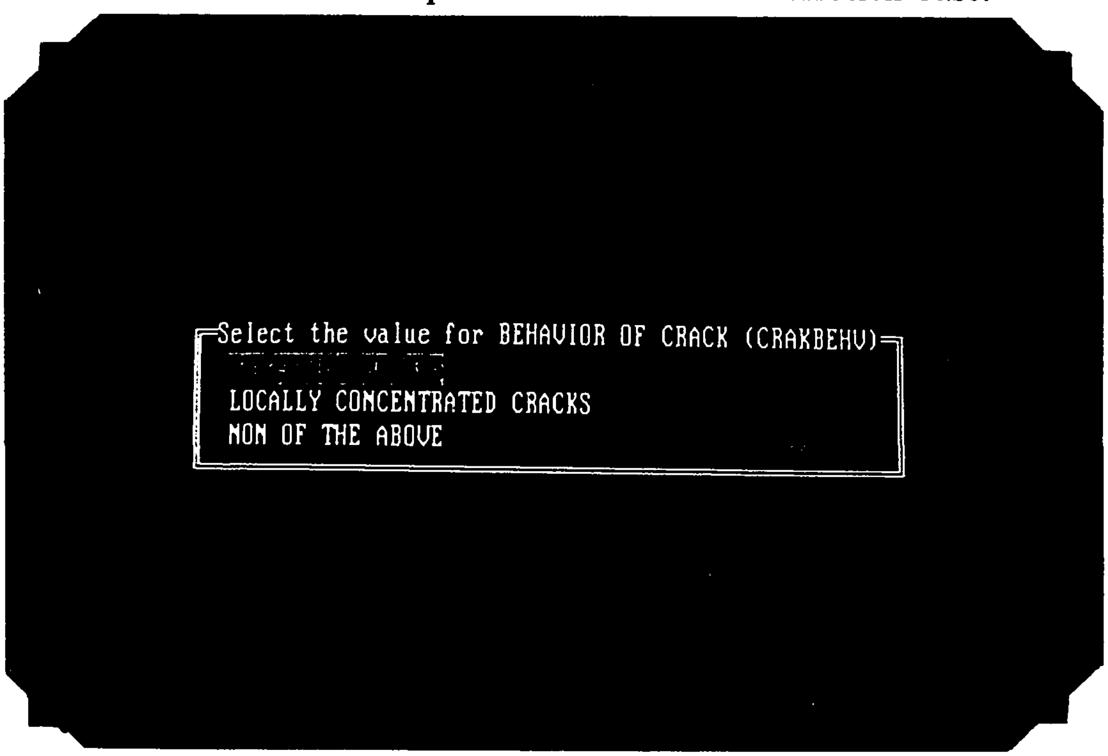


Plate 6.8.a Behavior of Crack Check Variable.

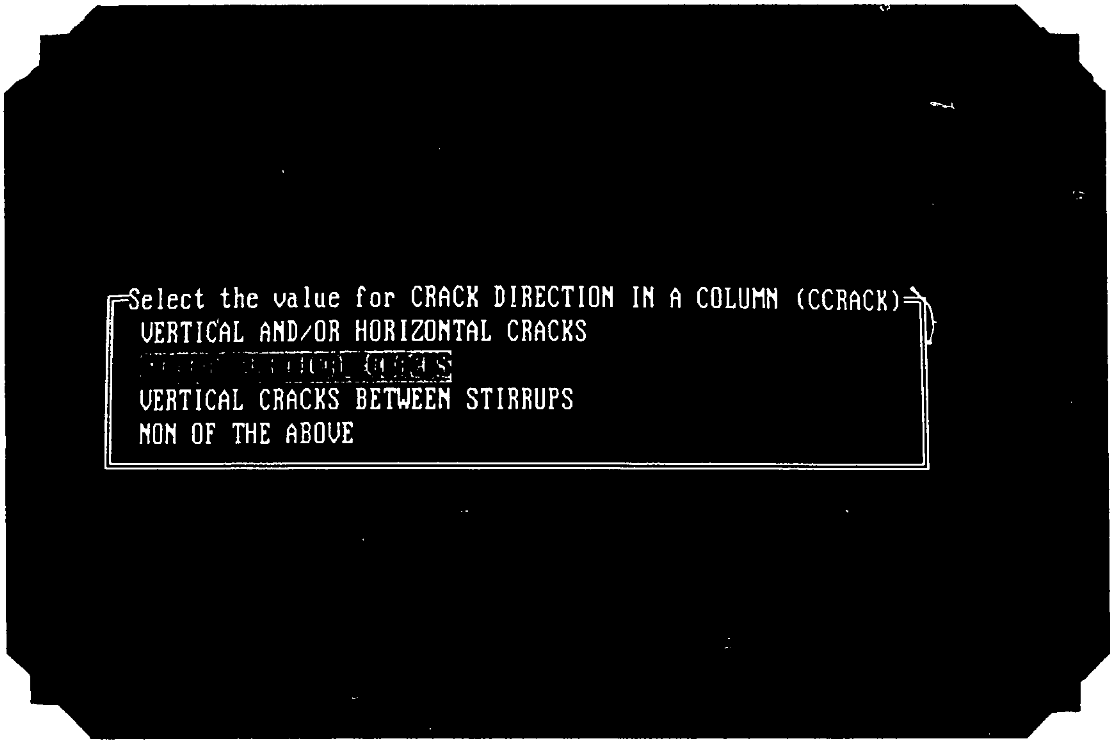


Plate 6.8.b Crack Direction Check Variable.

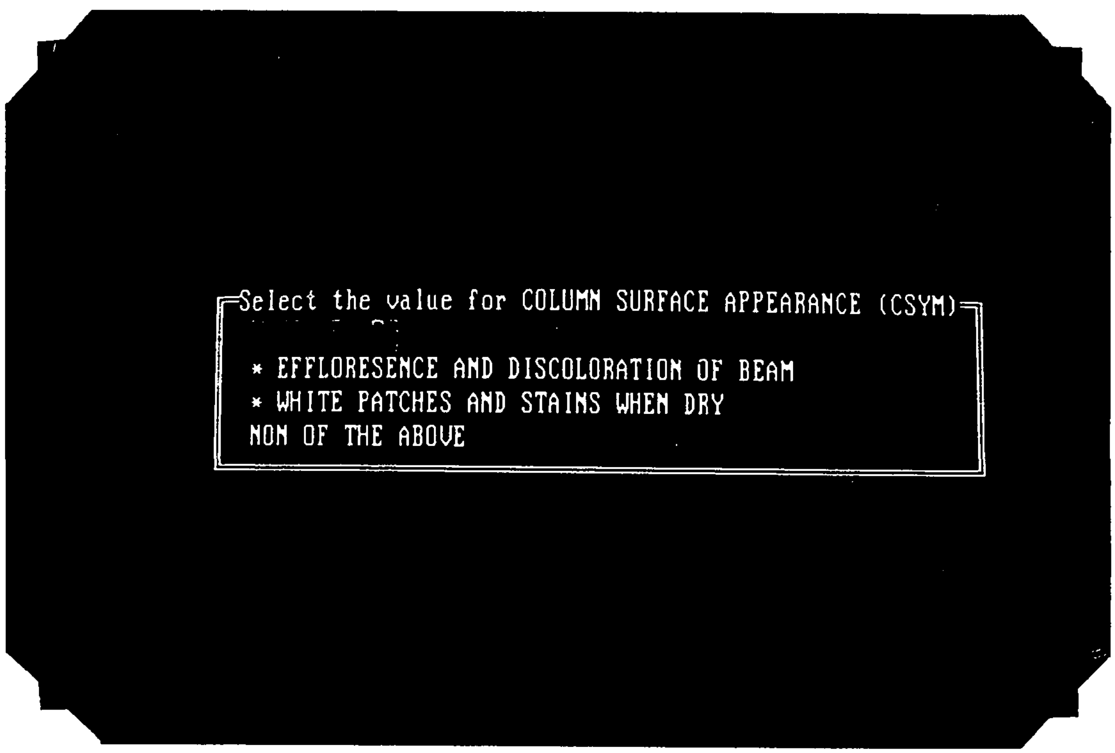


Plate 6.8.c Column Surface Appearance Check Variable.

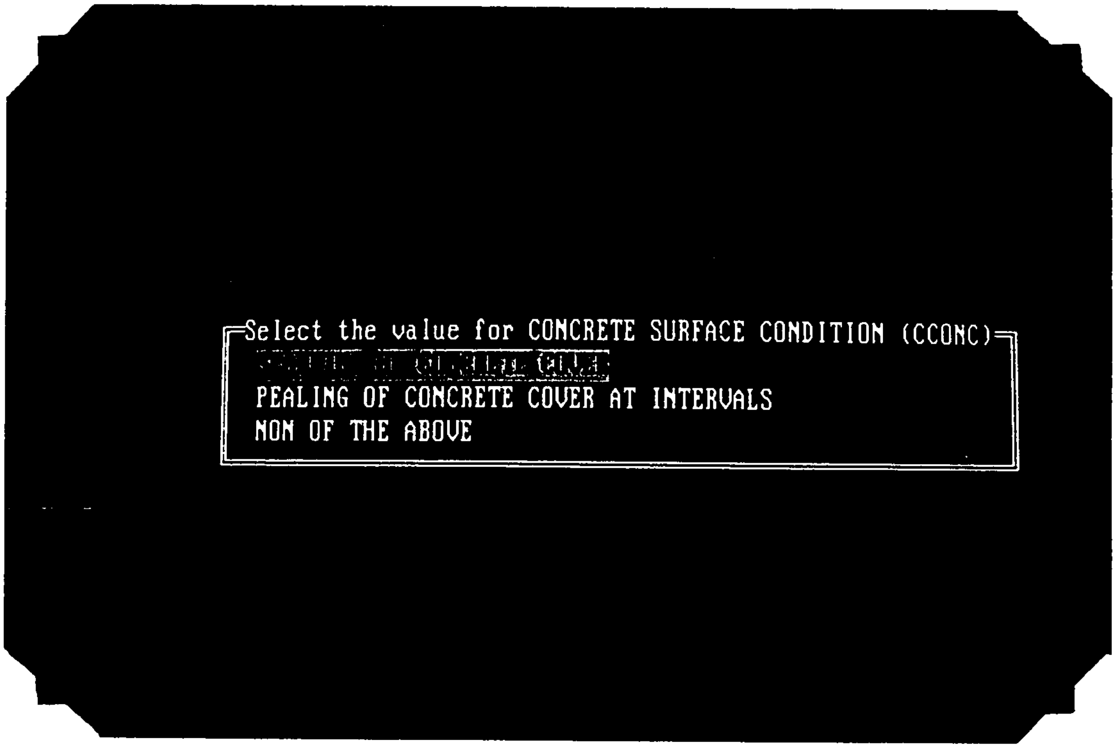


Plate 6.8.d Concrete Surface Condition Check Variable.

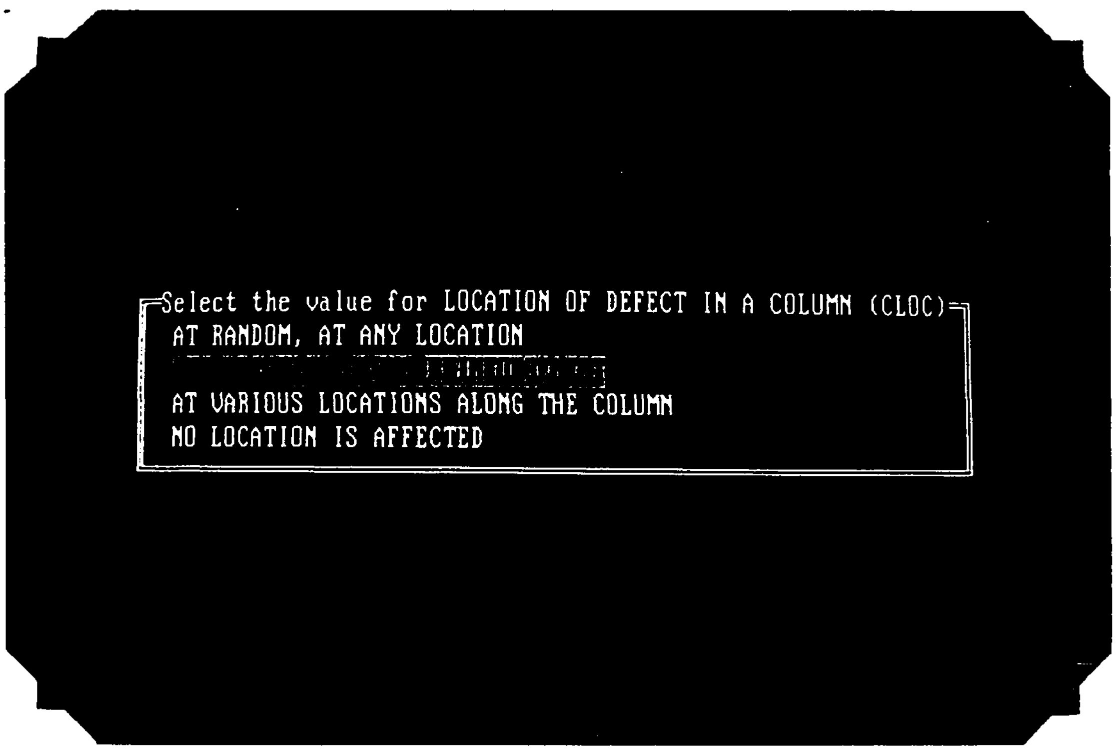


Plate 6.8.e Location of Crack in a Column Check Variable.

such as the one in Plate 6.9. The variables interpret the chemical analysis adopted for corrosion check. As done usually in common practice, these variables concentrate on the check of half cell potential, chlorides content, concrete alkalinity, and carbonation depth. the interactive dialogue with the user goes as follows; see Plates 6.10 (a, b, c, and e):

- (POT) Half cell potential?

  Potential > allowable.
- (CL) Chlorides content?

  Chlorides content > allowable.
- (PH) Concrete alkalinity?

  PH value is not within allowable.
- (CO) Depth of carbonation?

  Carborates depth > allowable.

Based on these input facts, the variable *PROBLEM* is assigned a value of "***corrosion of reinforcement***". The user is informed with this finding as well as a list of the required tests to diagnose this case. The developed forms are shown in Plates 6.11 (a and b).

The diagnostic process now commences. Search for the probable cause of corrosions sets forth the check for several related variables. The displayed quarrying windows interact with the user again and establish the required facts to reach a decision. Plates 6.12 (a, b, c, and d) illustrate corrosion related windows. When the user feeds the drawn facts obtained through inspection and field tests, *CONCEXS* builds up its

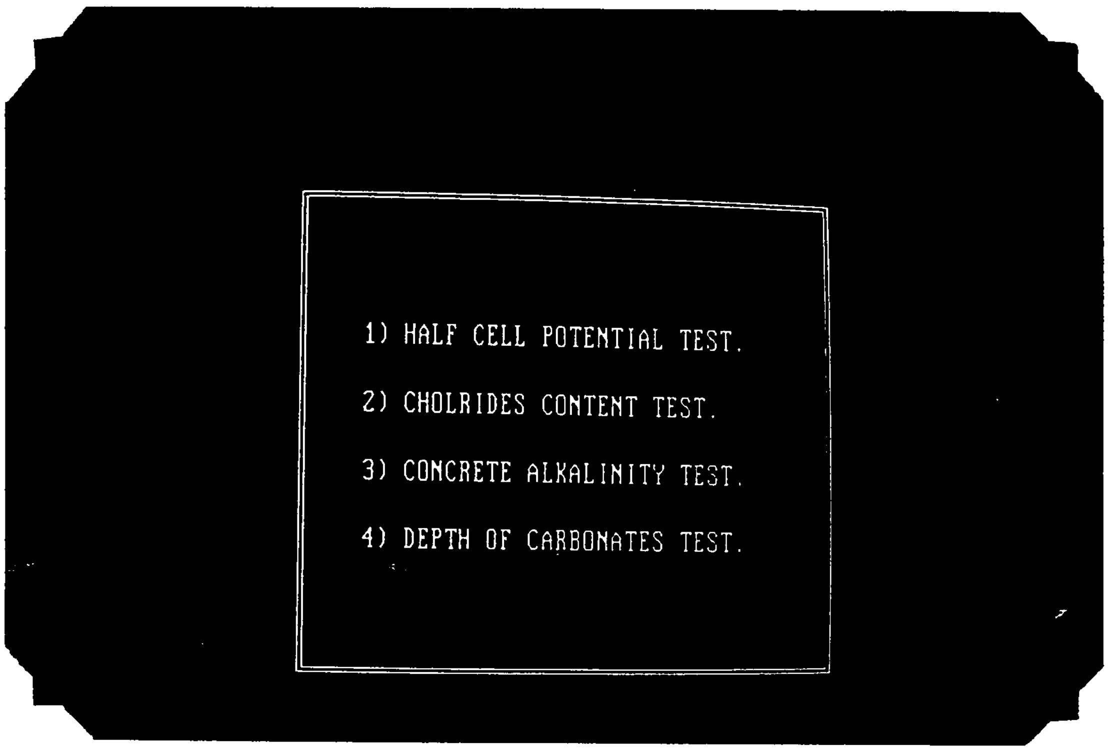


Plate 6.9 Required Tests to Ascertain Corrosion Occurrence.

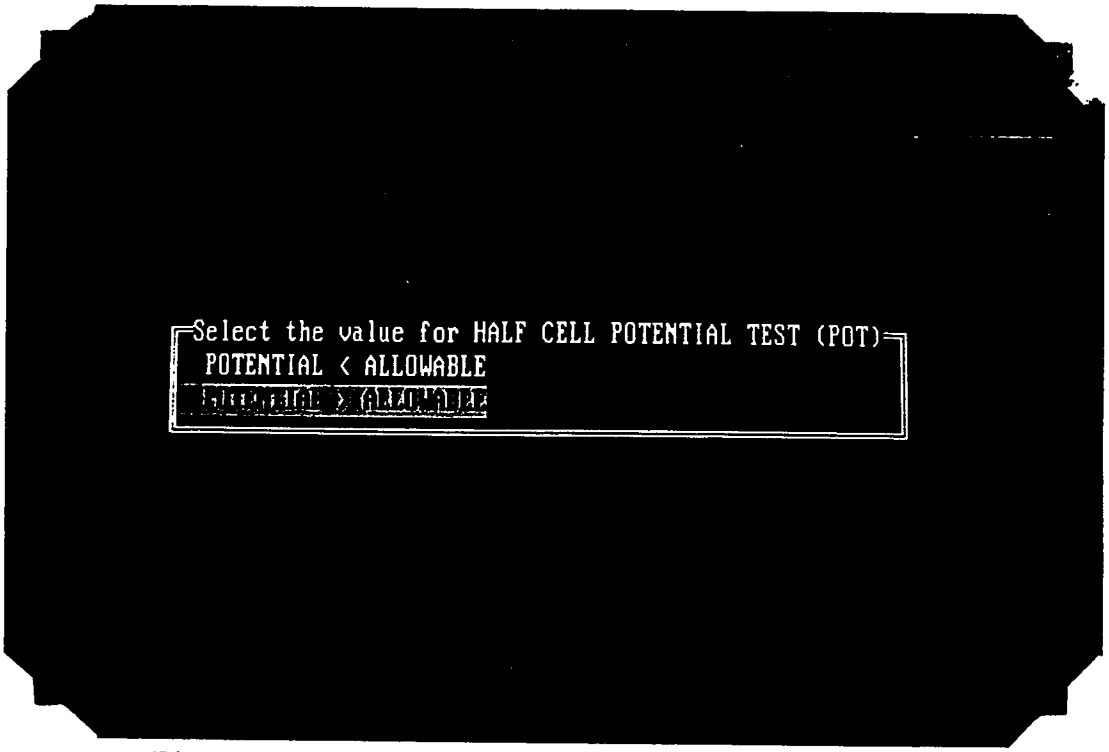


Plate 6.10.a Half Cell Potential Test Check Variable.

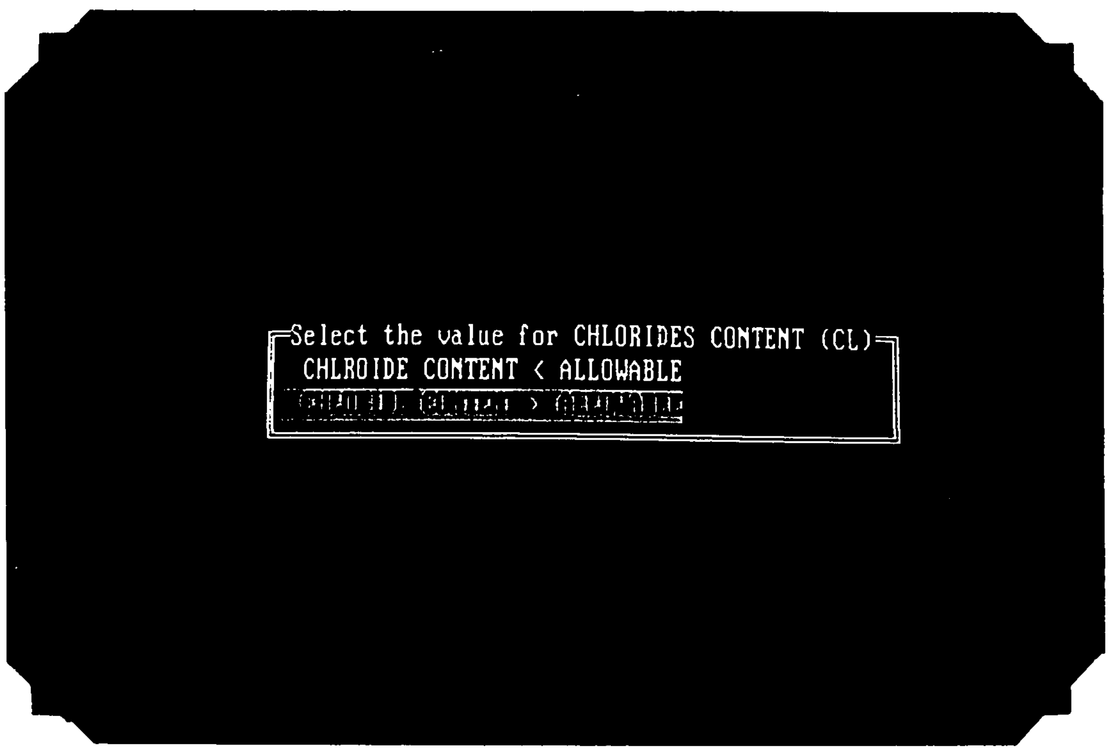


Plate 6.10.b C .hlorides Content Check Variable.

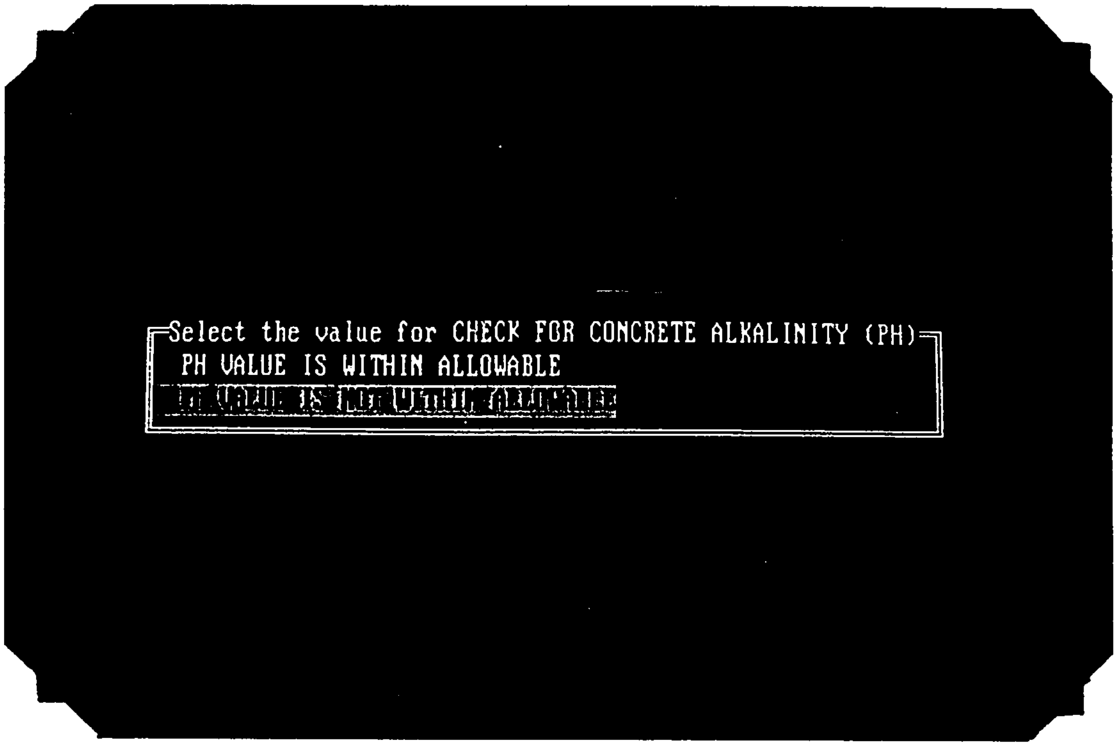


Plate 6.10.c Concrete Alkalinity Check Variable.

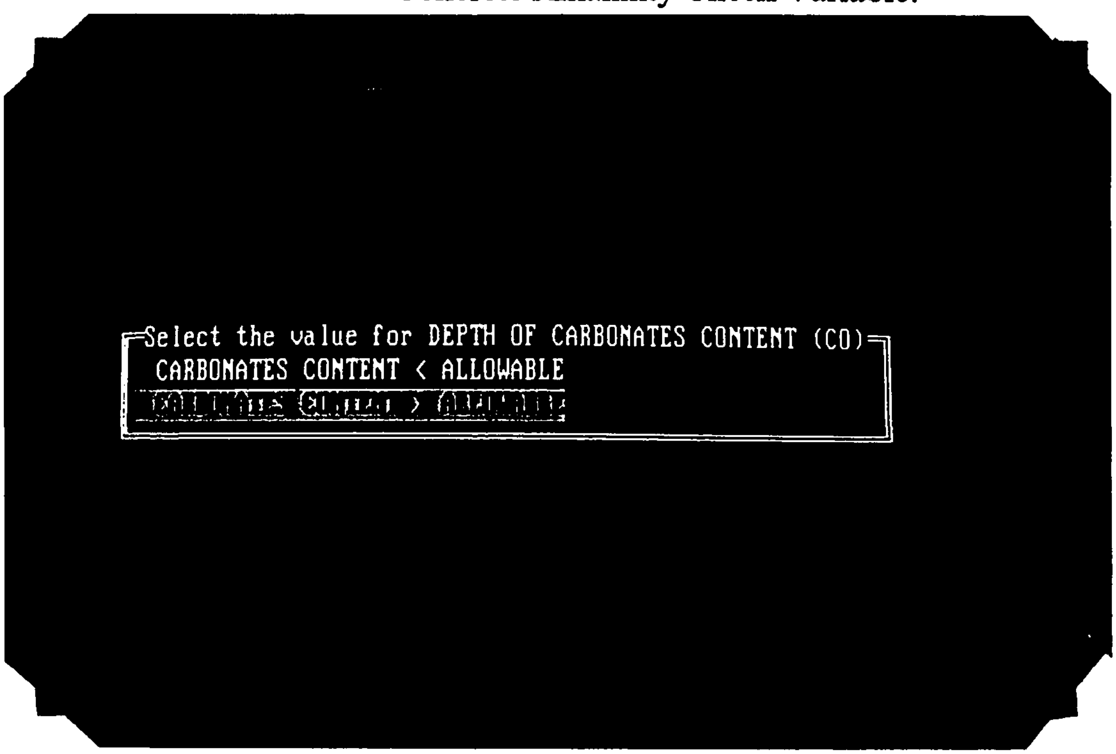


Plate 6.10.d Depth of Carbonation Check Variable.

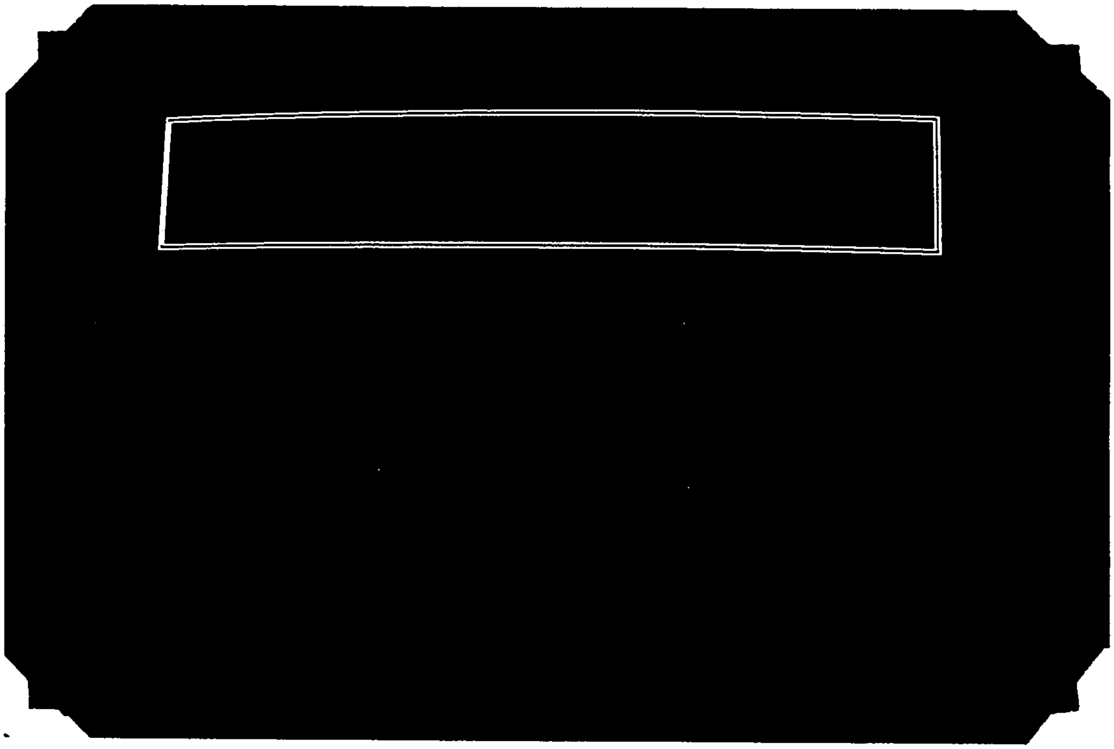


Plate 6.11.a Problem Sub goal is Known as Corrosion

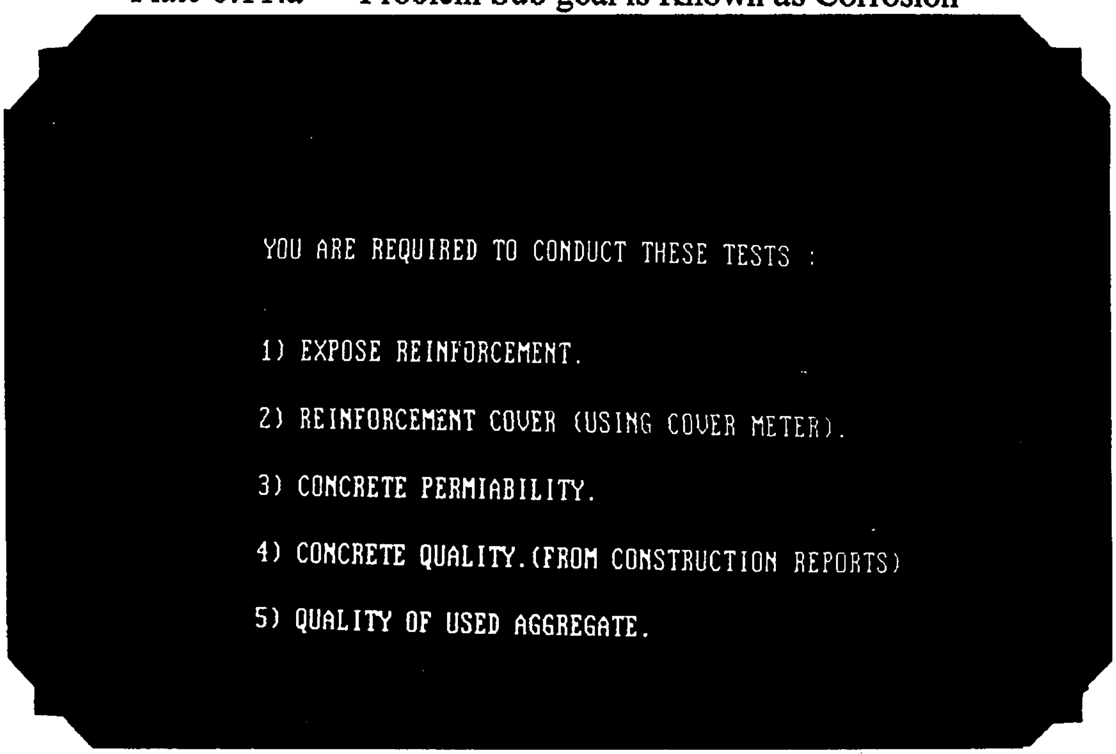


Plate 6.11.b Required Tests to Diagnose Corrosion of Reinforcement.

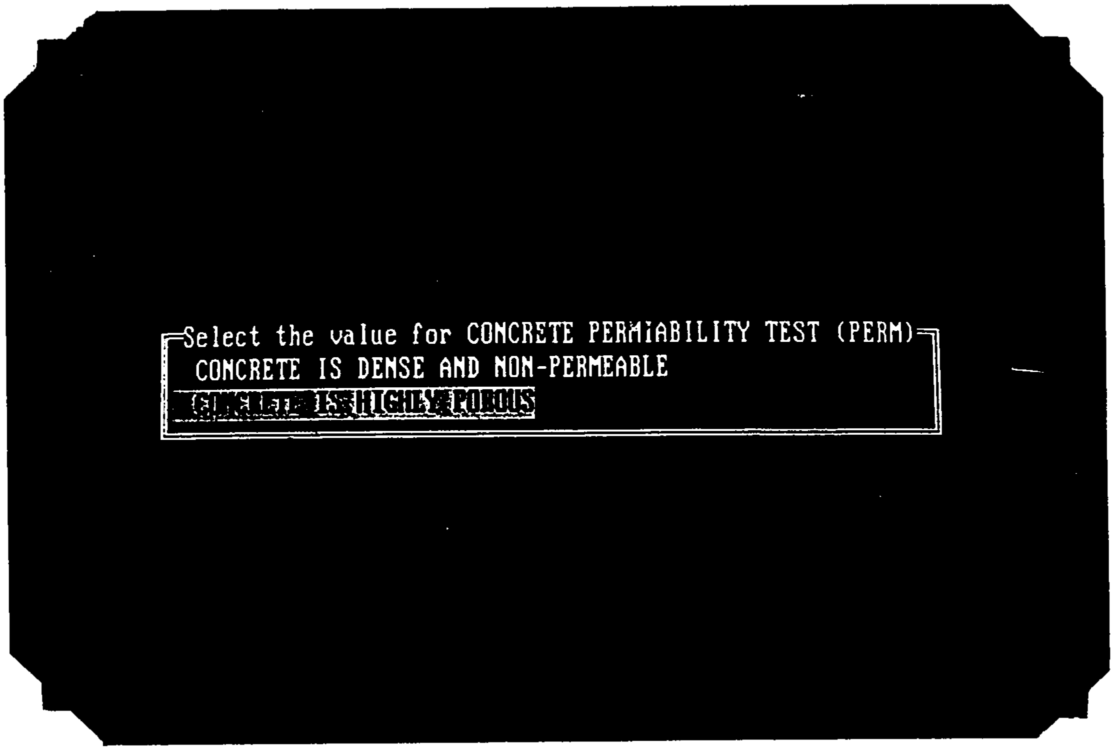


Plate 6.12.a Permeability Test Check Variable.

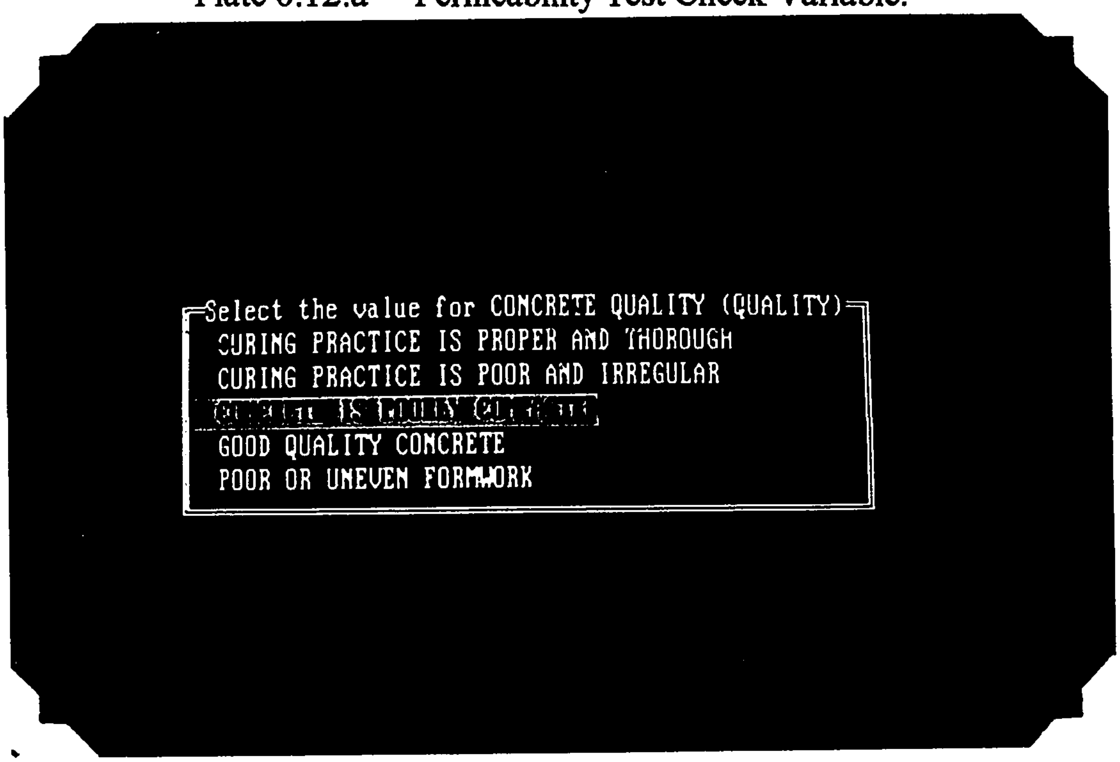


Plate 6.12.b Concrete Quality Check Variable.

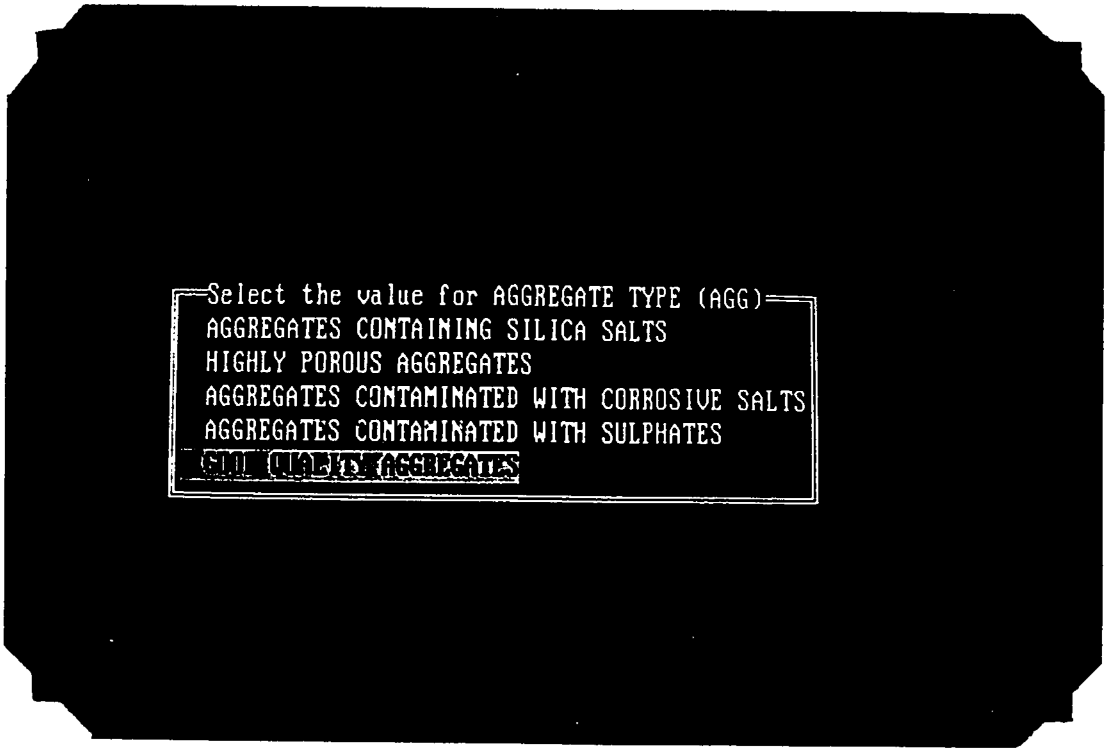


Plate 6.12.c Aggregate Type Check Variable.

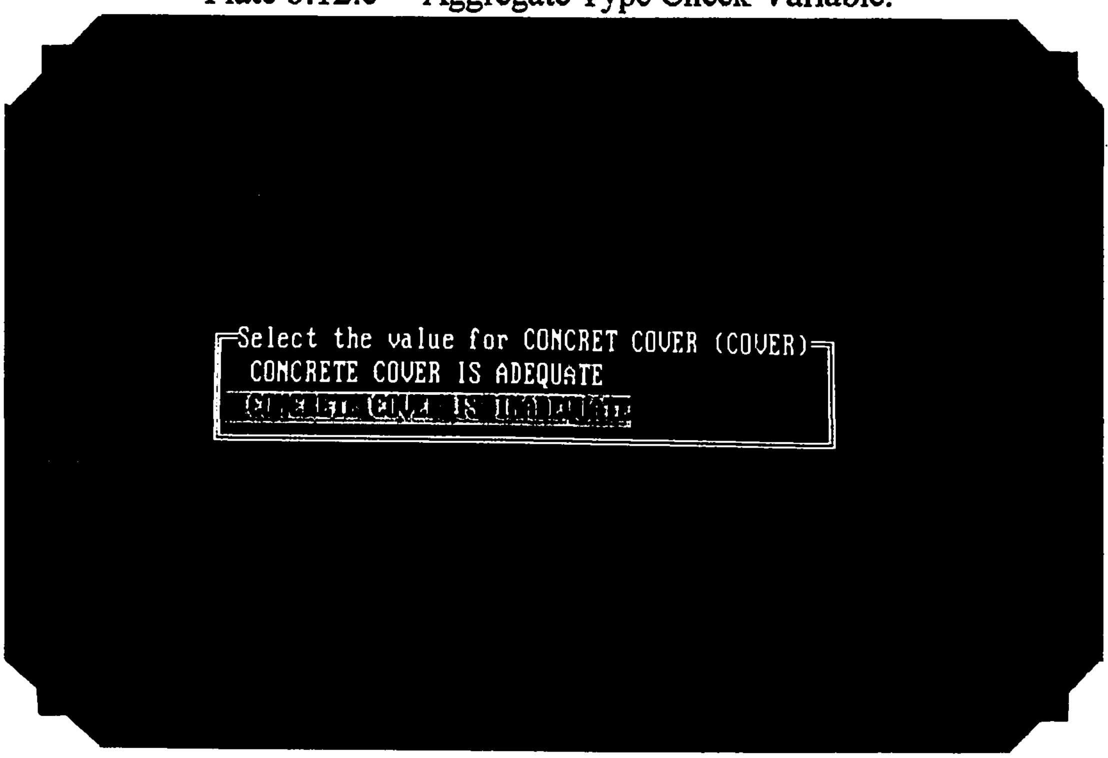


Plate 6.12.d Concrete Cover Check Variable.

reasoning strategy for corrosion diagnosis. A normal flow of the diagnostic process proceeds as follows:

- (PERM) Concrete permeability?

    Concrete is highly porous.

- (QUALITY) Concrete quality?

    Concrete is poorly compacted.

- (AGG) Aggregate type?

    Good quality aggregates.

- (COVER) Concrete cover to reinforcement?

    Concrete cover is inadeqaute.

An intensive search is performed through the system utilizing these values. The system tests the result of this search in view of its acquired expertise and formed into a reasonable decision value for the goal variable *CAUSE*. Diagnostic search for corrosion in columns based on the present conditions yields this cause:

Corrosion due to use of poor quality concrete liable to corrosion. And failure to provide sufficient concrete cover.

Plate 6.13 shows this output as it is produced to the user, which ends up the consultation session for a column corrosion case.

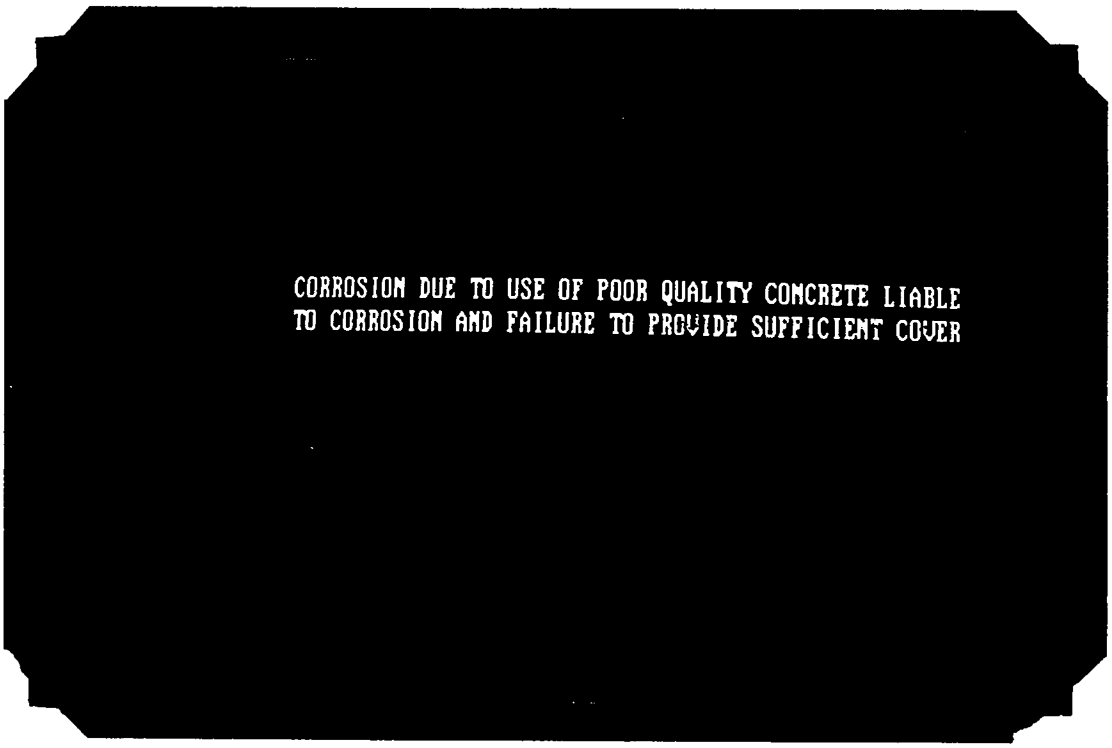


Plate 6.13 Decision Value for Column Corrosion Case.

As illustrated in this chapter, the developed knowledge based expert system was found to be very successful in the task it was designed for. It is clear that *CONCEXS* manipulates the diagnostic function thoroughly in a manner to cover real life attributes that frequently take place. Reasonably enough, it handles the factors that govern the domain of concrete deterioration within its acquired expertise. The system sounds to be able to derive rational diagnosis decisions similar to those usually drawn by human experts.

CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary and Conclusions

This thesis has focused on the development of a knowledge based system "CONCEXS", designed to perform the task of concrete diagnosis of existing structures. The knowledge base for the system handles concrete slabs, beams, and columns. This body of knowledge was acquired from local existing deterioration cases in Saudi Arabia. The domain of study for the system was found to be attractive: concrete diagnosis is a well-defined domain, the diagnostic procedures are well established, decisions of affecting factors can be rationally determined by governing conditions, documented cases exist, and the process depends on qualitative attributes.

CONCEXS at present, handles 16 different categories of concrete disintegration. These categories were thought to be due to 47 different actions. The body of knowledge in the system is generalized to a certain manageable extent to cover the vast array of information needed to facilitate its diagnostic function. CONCEXS' architecture is simulating the performance and analogy usually adopted by human concrete diagnosis experts whenever there is a need to seek there consent. Testing the system gave it its deserved credibility, as it was capable to derive successful decisions that disclosed the factors affecting concrete deterioration from within its built-in expertise.

During the course of this study, the development process passed over the evolutionary steps usually adopted for building knowledge based systems. It is the expandability feature of the system that gives it its real power. All over the development phases, future expansion was set as one of CONCEXS' targets. Whenever, any additional body of expertise is needed to be incorporated into the system, either the built-in variables can be utilized or, a reasonable new sets of attributes can be easily drawn and added to the system to enhance its performance.

As CONCEXS is handling a diagnostic task, informative knowledge screens were utilized to guide the user in systematic investigation of the problem. These forms given in the system's database, inform the user about the basic data that are needed by the system to in a particular consultation.

7.2 Recommendations

Going through the development cycle of CONCEXS, allows us to draw the following set of recommendations:

1. Although the developed system is at small level, the obtained results encourage the necessity to proceed with enlarging the system, enhancing it and intensifying the effort to collect a huge amount of knowledge, so that it can promise of a marketable nature.

2. Besides the importance and the benefits gained through adopting such a system for concrete diagnosis, the other aspects of concrete diagnosis should not be underestimated or given the due attention of required expertise and professional knowledge to arrive at reasonable diagnostic decisions.

3. The amount of knowledge involved in a system is the feature that gives it its real power. So, its recommended to build a well structured data base "concrete information facility", that can be incorporated to the system. Such a data base is thought to include detailed test procedures, additional material and design attributes, that can be called upon to illustrate the most relevant and comprehensive diagnostic decisions, which would undoubtedly ease any intended repair suggestions.

4. Incorporation of a graphical interface facility to the system would give it additional informative and friendly character. This facility will enhance the exchange of information between the user and the system, both in speed and ease of interaction. Adding apparent symptoms together in

a graphical representation would reduce the number of needed rules, and so number of questions to reach at a decision to identify the defect. Dealing with photos and charts is undoubtedly more professional than going over lengthy lines of dry text. Development of such interface, would overcome communication gaps that may arise, and would lead to wrong diagnosis.

5. Calling of sufficient expertise that can help in supplying the needed huge and wide scattered concrete diagnosis parameters would be a great asset to the system. For example, the domain of the system needs to incorporate additional building defects in foundations, walls, and finishing systems.

Appendices

A) Concrete inspection.

B) Defect Plates.

C) GURU specification.

D) Documented defect cases.

E) Implemented rules.

Appendix - A.1.a ACI Guide - 201

Appendix - A.1.b ACI Guide - 311

ACI 201.1R-68

(Revised 1984)

Guide for Making a Condition Survey of Concrete in Service

Reported by ACI Committee 201

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This guide provides a system for reporting on the condition of concrete in service. It includes a check list of the many details to be considered in making a report, and provides standard definitions of 40 terms associated with the durability of concrete. Its purpose is to establish a uniform system for evaluating the condition of concrete.

Keywords: buildings; concrete construction; concrete durability; concrete pavements; concretes; corrosion; cracking (fracturing); deterioration; environment; freeze-thaw durability; inspection; joints; popouts; quality control; scaling; serviceability; spalling; strength; surveys (data collection).

This document has been approved for use by agencies of the Department of Defense and for listing in the DoD Index of Specifications and Standards.

■ A CHECK LIST IS provided for making a survey of the condition of concrete. The list is designed to be used in recording the history of a concrete project from inception through completion and subsequent life of the structure or pavement.

While it probably will be used most often in connection with the survey of concrete that is showing some degree of distress, its application is recommended for all important concrete structures. In any case, records of the materials and construction practices used should be maintained because they are difficult to obtain at a later date.

The committee has attempted to include all pertinent items that might have a bearing on the performance of the concrete. However, those making the survey should not limit their investigation to the items listed, thereby overlooking or ignoring other possible contributing factors. Simply following the guide will not eliminate the need for intelligent observation and the use of sound judgment.

Those performing the survey should be experienced and competent in this field. In addition to verbal descriptions, numerical data obtained by laboratory tests and field measurements should be provided wherever possible. Photographs, including a scale to indicate linear dimensions, are of great value in showing condition of structure.

One of the objects of a condition survey is to provide information that will be of value in the construction of more economical, serviceable structures. The survey may show causes of deterioration or lack of need of expensive materials or construction methods. The check list should be used in conjunction with the following:

1. ACI Committee 311, "Recommended Practice for Concrete Inspection (ACI 311-75)," American Concrete Institute, 1975, 6 pp. Also *ACI Manual of Concrete Practice*, Part 2.
2. ACI Committee 201, "Guide to Durable Concrete"—ACI 201.2R-77, ACI JOURNAL, *Proceedings* V. 74, No. 12, Dec. 1977, pp. 573-609. Also *ACI Manual of Concrete Practice*, Part 1.

CHECK LIST

1. Description of structure or pavement

1.1. Name, location, type, and size

1.2. Owner, project engineer, contractor, when built

1.3. Design

1.3.1. Architect and/or engineer

1.3.2. Intended use and history of use

1.3.3. Special features

1.4. Photographs

1.4.1. General view

1.4.2. Detailed close-ups of condition of area

1.5. Sketch map — orientation showing sunny and shady walls and well and poorly drained regions

2. Present condition of structure

2.1. Over-all alignment of structure

2.1.1. Settlement

2.1.2. Deflection

2.1.3. Expansion

2.1.4. Contraction

2.2. Portions showing distress (beams, columns, pavement, walls, etc. Subjected to strains and pressures)

2.3. Surface condition of concrete

2.3.1. General (good, satisfactory, poor, etc.)

2.3.2. Cracks

2.3.2.1. Location and frequency

2.3.2.2. Type and size

2.3.2.3. Leaching, stalactites

2.3.3. Scaling

2.3.3.1. Area, depth

2.3.3.2. Type (see definition)

2.3.4. Spalls and popouts

2.3.4.1. Number, size and depth

2.3.4.2. Type (see definitions)

2.3.5. Extent of corrosion or chemical attack

2.3.6. Stains

2.3.7. Exposed steel

2.3.8. Previous patching or other repair

2.4. Interior condition of concrete

2.4.1. Strength of cores

2.4.2. Density of cores

2.4.3. Moisture content (degree of saturation)

2.4.4. Evidence of alkali-aggregate or other reaction

2.4.5. Bond to aggregate, reinforcing steel, joints

2.4.6. Pulse velocity

2.4.7. Volume change

2.4.8. Air content and distribution

2.4.9. Chloride Ion Content

2.4.10. Cover Reinforcing Steel

2.4.11. Half Cell Potential to Reinforcing Steel

2.4.12. Delaminated Areas

3. Nature of loading and detrimental elements

3.1. Exposure

3.1.1. Environment — arid, subtropical, marine, freshwater, industrial, etc.

3.1.2. Weather — (July and January mean temperatures, mean annual rainfall and months in which 60 percent of it occurs)

3.1.3. Freezing and thawing

3.1.4. Wetting and drying

3.1.5. Drying under dry atmosphere

3.1.6. Chemical attack—Sulfates, acids, chloride

3.1.7. Abrasion, erosion, cavitation

3.1.8. Electric currents

3.2. Drainage

3.2.1. Flashing

3.2.2. Weepholes

3.2.3. Contour

3.3. Loading
3.3.1. Dead
3.3.2. Live
3.3.3. Impact
3.3.4. Vibration
3.3.5. Traffic index
3.3.6. Other
3.4. Soils (foundation conditions)
3.4.1. Stability
3.4.2. Expansive soil
3.4.3. Settlement
3.4.4. Restraint

4. Original condition of structure
4.1. Condition of formed and finished surfaces
4.1.1. Smoothness
4.1.2. Air pockets
4.1.3. Sand streaks
4.1.4. Honeycomb
4.1.5. Soft areas
4.2. Early structural defects
4.2.1. Cracking
4.2.1.1. Plastic shrinkage
4.2.1.2. Settlement
4.2.1.3. Cooling
4.2.2. Curling
4.2.3. Structural settlement

5. Materials of construction
5.1. Hydraulic cement
5.1.1. Type and source
5.1.2. Chemical analysis (obtain certified test data if available)
5.1.3. Physical properties
5.2. Aggregates
5.2.1. Coarse
5.2.1.1. Type, source and mineral composition (representative sample available)
5.2.1.2. Quality characteristics
5.2.1.2.1. Percentage of deleterious material
5.2.1.2.2. Percentage of potentially reactive materials
5.2.1.2.3. Coatings, texture, and particle shape
5.2.1.2.4. Gradation, soundness, hardness
5.2.1.2.5. Other properties as specified in ASTM Designation C 33 (C 330 — for lightweight aggregate)
5.2.2. Fine aggregate
5.2.2.1. Type, source, and mineral composition (representative sample available)
5.2.2.2. Quality characteristics
5.2.2.2.1. Percentage of deleterious material
5.2.2.2.2. Percentage of potentially reactive materials
5.2.2.2.3. Coatings, texture and particle shape
5.2.2.2.4. Gradation, soundness and hardness
5.2.2.2.5. Other properties as specified in ASTM Designation C33 (C330 for lightweight aggregate)
5.3. Mixing water
5.3.1. Source and quality
5.4. Air-entraining agents
5.4.1. Type and source
5.4.2. Composition
5.4.3. Amount
5.4.4. Manner of introduction
5.5. Admixtures
5.5.1. Mineral admixture
5.5.1.1. Type and source
5.5.1.2. Physical properties
5.5.1.3. Chemical properties
5.5.2. Chemical admixture
5.5.2.1. Type and source
5.5.2.2. Composition
5.5.2.3. Amount
5.6 Concrete
5.6.1. Mixture proportions
5.6.1.1. Cement content
5.6.1.2. Proportions of each size aggregate
5.6.1.3. Water-cement ratio
5.6.1.4. Water content
5.6.1.5. Chemical admixture
5.6.1.6. Mineral admixture
5.6.1.7. Air-entraining agent
5.6.2. Properties of fresh concrete
5.6.2.1. Slump
5.6.2.2. Percent air
5.6.2.3. Workability
5.6.2.4. Unit weights
5.6.2.5. Temperature
5.6.3. Type
5.6.3.1. Cast-in-place
5.6.3.2. Precast
5.6.3.3. Prestressed
5.6.4. Reinforcement
5.6.4.1. Yield strength
5.6.4.2. Thickness of cover
5.6.4.3. Presence of stirrups
5.6.4.4. Use of welding

6. Construction practices
6.1. Storage and processing of materials
6.1.1. Aggregates
6.1.1.1. Grading
6.1.1.2. Washing
6.1.1.3. Storage
6.1.1.3.1. Stockpiling
6.1.1.3.2. Bins

6.1.2. Cement and admixtures
6.1.2.1. Storage
6.1.2.2. Handling
6.1.3. Reinforcing steel and inserts
6.1.3.1. Storage
6.1.3.2. Placement
6.2. Forming
6.2.1. Type
6.2.2. Bracing
6.2.3. Coating
6.2.4. Insulation
6.3. Concreting operation
6.3.1. Batching plant
6.3.1.1. Type—automatic, manual, etc.
6.3.1.2. Condition of equipment
6.3.1.3. Batching sequence
6.3.2. Mixing
6.3.2.1. Type—central mix, truck mix, job mix, shrink mix, etc.
6.3.2.2. Condition of equipment
6.3.2.3. Mixing time
6.3.3. Method of transporting—trucks, buckets, chutes, pumps, etc.
6.3.4. Placing
6.3.4.1. Methods—conventional, underwater slipform, etc.
6.3.4.2. Equipment—buckets, elephant trunks, vibrators, etc.
6.3.4.3. Weather conditions—time of year, rain, snow, dry wind, temperature, humidity, etc.
6.3.4.4. Site conditions—cut, fill, presenc of water, etc.
6.3.4.5. Construction joints
6.3.5. Finishing
6.3.5.1. Type—slabs, floors, pave: purtenances
6.3.5.2 Method—hand or machin
6.3.5.3. Equipment—screeds, flo: els. straight-edge, belt, etc.
6.3.5.4. Additives, hardeners. w: coat, coloring, etc.
6.3.6. Curing Procedures
6.3.6.1. Method—water, coverin compounds
6.3.6.2. Duration
6.3.6.3. Efficiency
6.3.7. Form removal (time of remova

7. Initial physical properties of hardened
7.1. Strength—compressive, flexural, modulus
7.2. Density
7.3. Percentage and distribution of air
7.4. Volume change potential
7.4.1. Shrinkage or contraction
7.4.2. Expansion or swelling
7.4.3. Creep
7.5. Thermal properties

APPENDIX

DEFINITION OF TERMS ASSOCIATED WITH THE DURABILITY OF CONCRETE

A.1 Cracks: An incomplete separation into one or more parts with or without space between.

A.1.1. Cracks will be classified by direction, width and depth. The following adjectives can be used: longitudinal, transverse, vertical, diagonal, and random. Three width ranges are suggested as follows: fine—generally less than 1 mm; medium—between 1 and 2 mm; wide—over 2 mm (see Fig. A.1.1.a through A.1.1.h).

A.1.2. *Pattern cracking*: Fine openings on concrete surfaces in the form of a pattern; resulting from a decrease in volume of the material near the surface, or increase in volume of the material below the surface, or both (see Fig. A.1.2.a through A.1.2.c).

A.1.3. *Checking*: Development of shallow cracks at closely spaced but irregular intervals on the surface of mortar or concrete (see Fig. A.1.3).

A.1.4. *Hairline cracking*: Small cra random pattern in an exposed concrete su

A.1.5. *D-cracking*: The progressive for on a concrete surface of a series of fine cr. rather close intervals, often of random pa but in highway slabs paralleling edges, join cracks and usually curving across slab (see Fig. A.1.5).

A.2. Deterioration: Deterioration is any a change of normal mechanical, physical and cal properties either on the surface or whole body of concrete generally through s tion of its components.

A.2.1. *Disintegration*: Deterioration small fragments or particles due to any caus Fig. A.2.1).

A.2.2. *Distortion*: Any abnormal def tion of concrete from its original shape (se A.2.2).

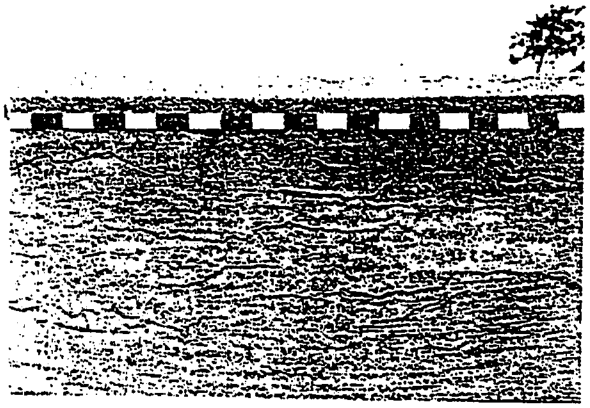


Fig. A.1.1.a—Longitudinal cracks (medium)

Fig. A.1.1.b—Transverse cracks (wide)

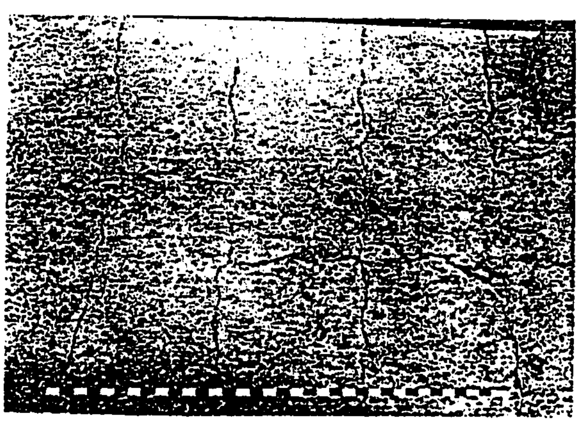


Fig. A.1.1.c—Transverse cracks (fine)

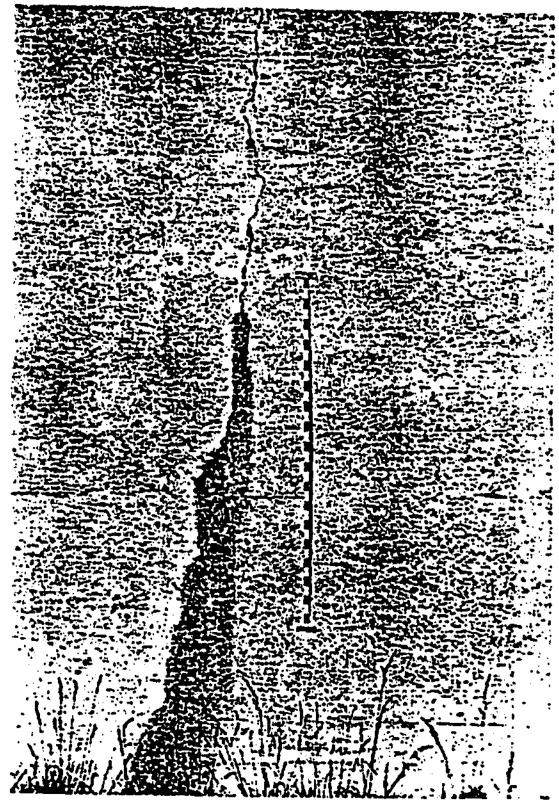


Fig. A.1.1.d—Vertical crack (medium)

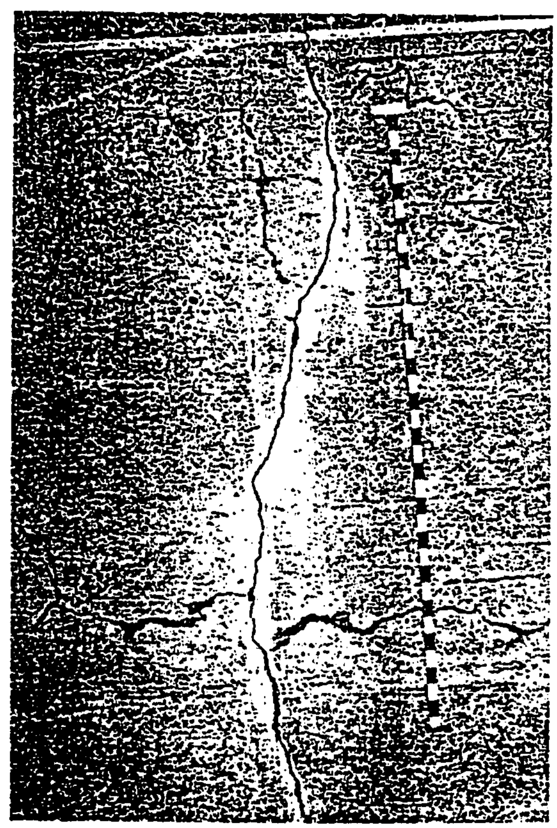


Fig. A.1.1.e—Vertical crack (wide)

Fig. A.1.1.f—Diagonal cracks (wide)

Fig. A.1.1.g—Random cracks (wide)

Fig. A.1.1.h—Random cracks (medium)

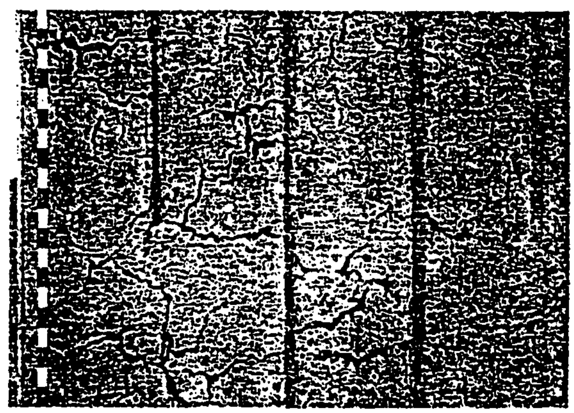


Fig. A.1.2.a—Pattern cracking (fine)

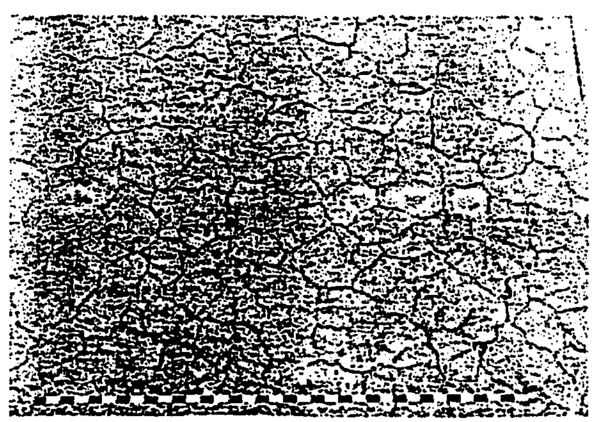


Fig. A.1.2.b—Pattern cracking (medium)

Fig.A.1.2.c—Pattern cracking (wide)

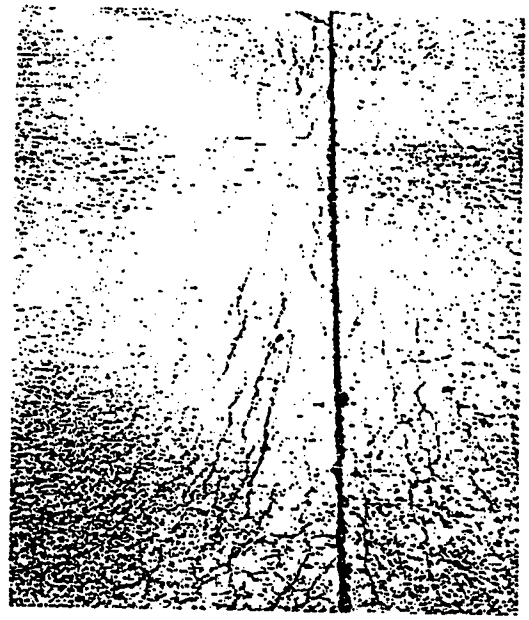


Fig. A.1.5—D-cracking

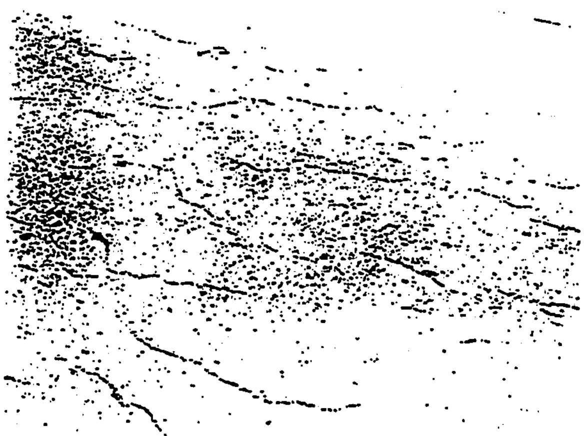


Fig. A.1.3—Checking (medium)

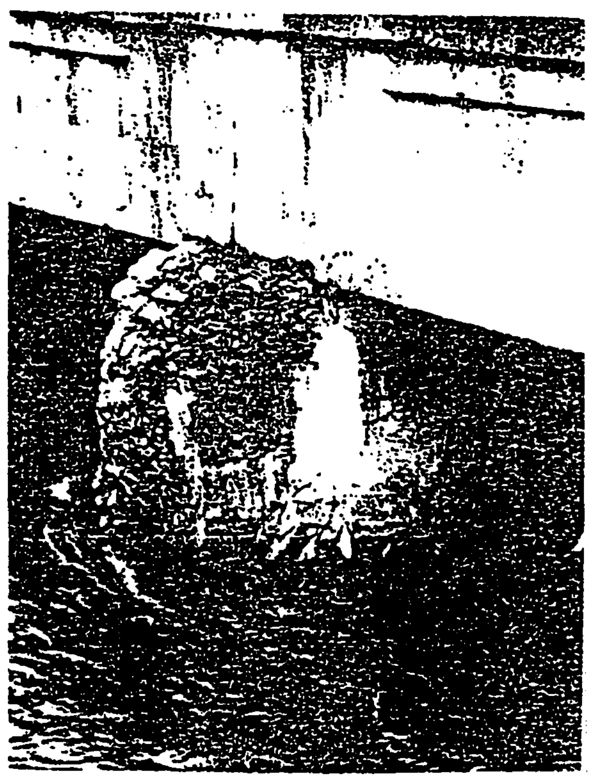


Fig. A.2.1—Disintegration

A.2.3. *Efflorescence*: A deposit of salts, usually white, formed on a surface, the substance having emerged from below the surface.

A.2.4. *Exudation*: A liquid or viscous gel-like material discharged through a pore, crack or opening in the surface (see Fig. A.2.4.a, A.2.4.b and A.2.5).

A.2.5. *Incrustation*: A crust or coating generally hard formed on the surface of concrete or masonry construction (see Fig. A.2.5)

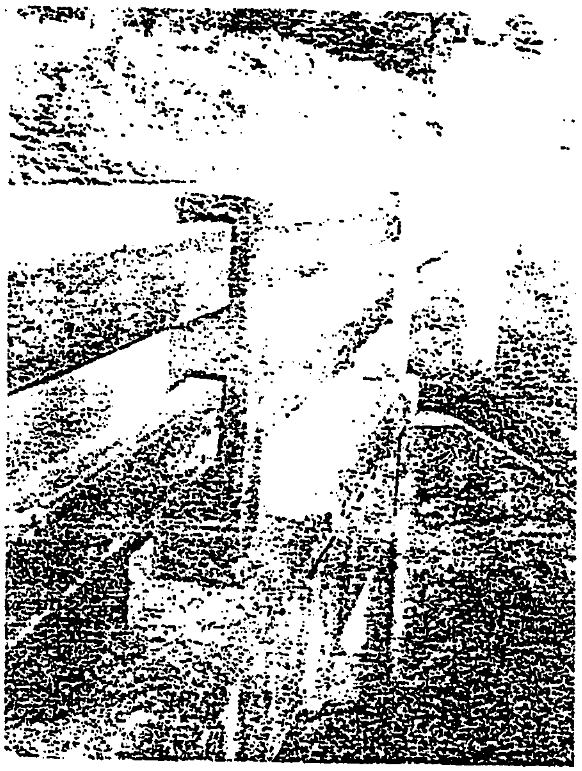


Fig. A.2.2—Distortion

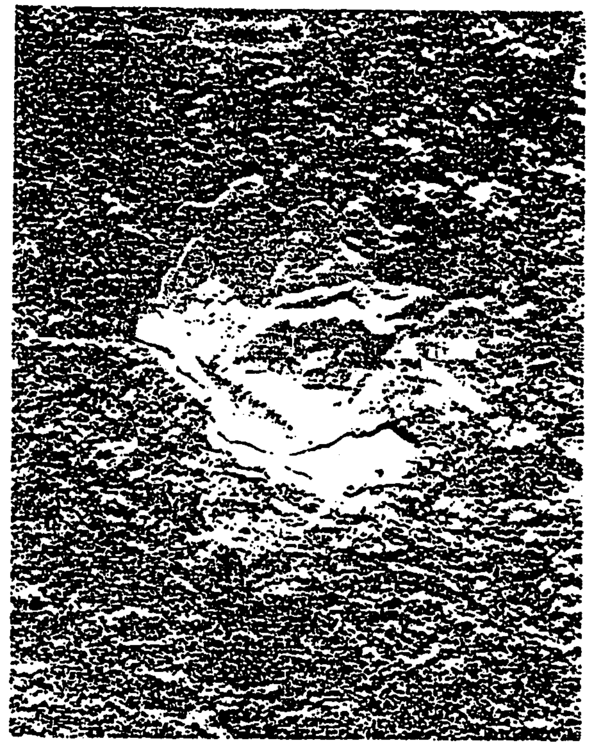


Fig. A.2.4.b—Exudation

Fig. A.2.4.a—Exudation

Fig. A.2.5—Exudation and incrustation

A.2.6. *Pitting:* Development of relatively small cavities in a surface, due to phenomena such as corrosion or cavitation, or, in concrete, localized disintegration.

A.2.7. *Popout:* The breaking away of small portions of a concrete surface due to internal pressure which leaves a shallow, typical conical, depression (see Fig. A.2.7).

A.2.7.1. *Popouts, small:* Popouts leaving holes up to 10 mm in diameter, or the equivalent (see Fig. A.2.7.1).

A.2.7.2. *Popouts, medium:* Popouts leaving holes between 10 and 50 mm in diameter, or equivalent (see Fig. A.2.7.2).

A.2.7.3. *Popouts, large:* Popouts leaving holes greater than 50 mm in diameter, or the equivalent (see Fig. A.2.7.3).

A.2.8. *Erosion:* Deterioration brought about by the abrasive action of fluids or solids in motion (see Fig. A.2.8).

A.2.9. *Scaling:* Local flaking or peeling away of the near surface portion of concrete or mortar.

A.2.9.1. *Peeling:* A process in which thin flakes of mortar are broken away from a concrete surface; such as by deterioration or by adherence of surface mortar to forms as forms are removed (see Fig. A.2.9.1.a and A.2.9.1.b).

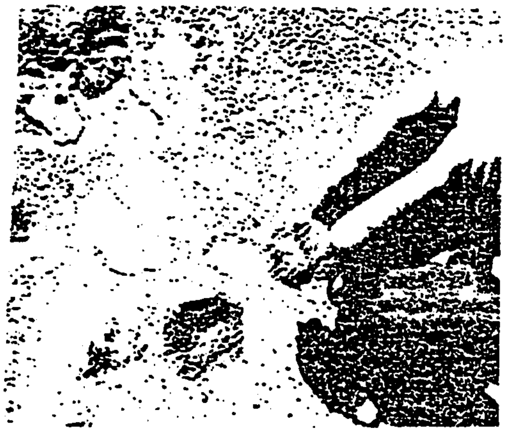


Fig. A.2.7—Popout

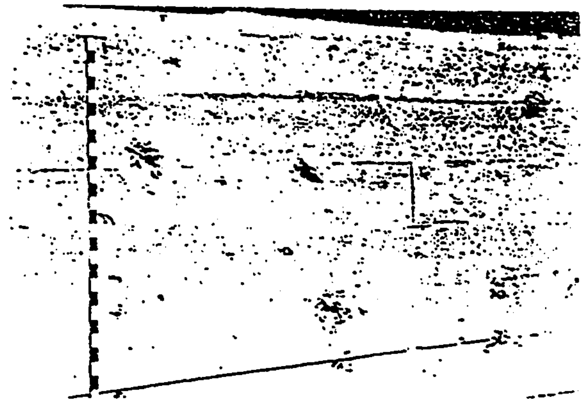


Fig. A.2.7.2—Popouts (medium)

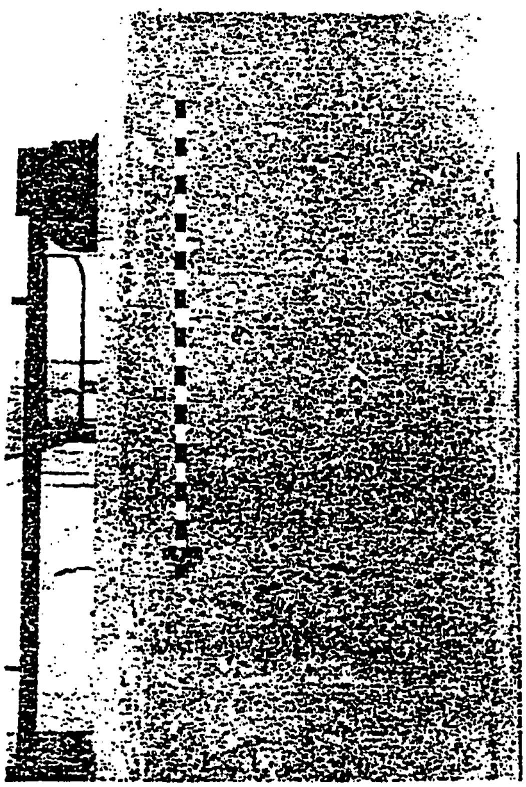


Fig. A.2.7.1—Popouts (small)

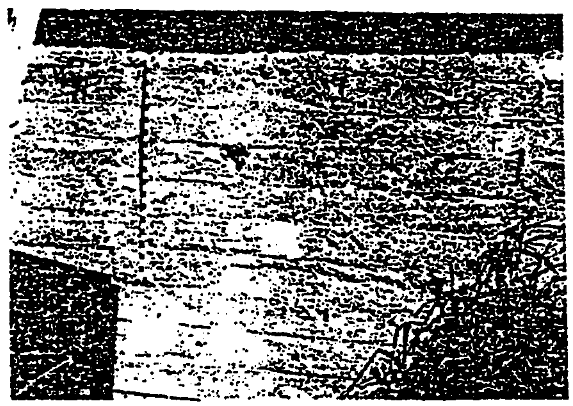


Fig. A.2.7.3—Popouts (large)

A.2.9.2. *Scaling, light*: Loss of surface mortar without exposure of coarse aggregate (see Fig. A.2.9.2.a and A.2.9.2.b).

A.2.9.3. *Scaling, medium:* Loss of surface mortar up to 5 to 10 mm in depth and exposure of coarse aggregate (see Fig. A.2.9.3.a and A.2.9.3.b).

A.2.9.4. *Scaling, severe:* Loss of surface mortar 5 to 10 mm in depth with some loss of mortar surrounding aggregate particles 10 to 20 mm in

Fig. A.2.8—Erosion

depth, so that aggregate is clearly exposed and stands out from the concrete (see Fig. A.2.9.4.a and A.2.9.4.b).

A.2.9.5. *Scaling, very severe:* Loss of coarse aggregate particles as well as surface mortar and mortar surrounding aggregate, generally greater than 20 mm in depth (see Fig. A.2.9.5.a and A.2.9.5.b).

A.2.10. *Spall:* A fragment, usually in the shape of a flake, detached from a larger mass by a blow, by the action of weather, by pressure, or by expansion within the large mass.

A.2.10.1. *Small spall:* A roughly circular or oval depression generally not greater than 20 mm in depth nor greater than about 150 mm in any dimension, caused by the separation of a portion of the surface concrete (see Fig. A.2.10.1).

A.2.10.2. *Large spall:* May be roughly circular or oval depression, or in some cases an elongated depression over a reinforcing bar, generally 20 mm or more in depth and 150 mm or greater in any dimension, caused by a separation of the surface concrete (see Fig. A.2.10.2).

A.2.11. *Joint spall:* Elongated cavity along a joint (see Fig. A.2.11.a and A.2.11.b).

Fig. A.2.9.1.a—Close-up of peeling

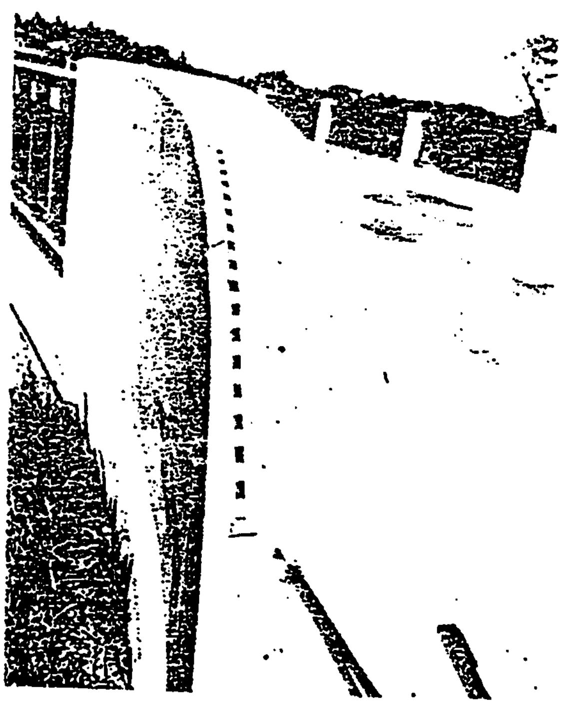


Fig. A.2.9.1.b—Peeling on bridge abutment

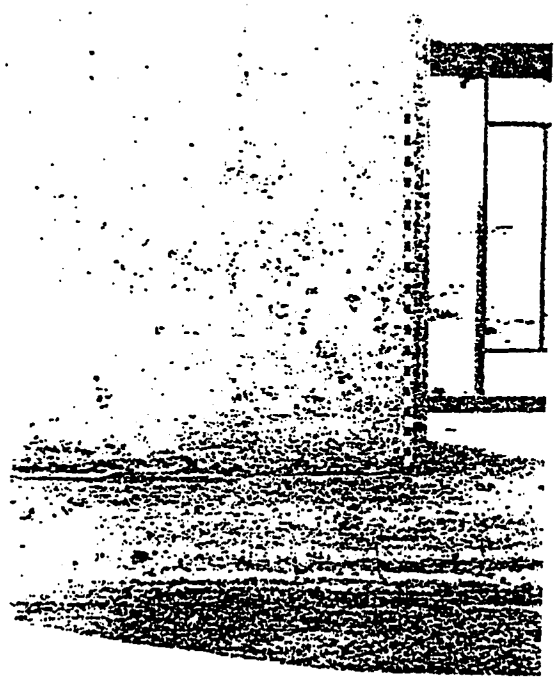


Fig. A.2.9.2.a—Scaling (light)

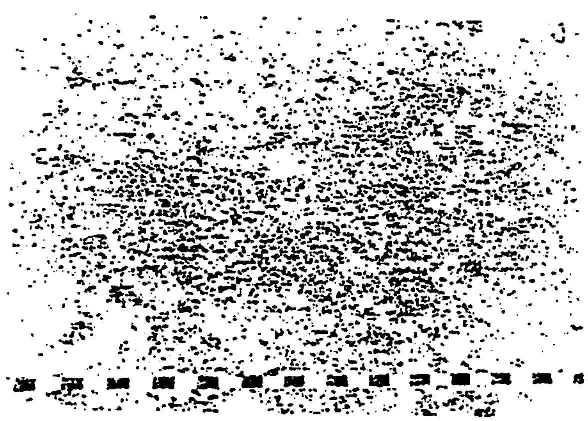


Fig. A.2.9.2.b—Close-up of scaling (light)

A.2.12. *Drummy area*: Area of concrete surface which gives off a hollow sound when struck.

A.2.13. *Stalactite*: A downward pointing formation, hanging from the surface of concrete, shaped like an icicle.

A.2.14. *Stalagmite*: As stalactite, but upward formation.

A.2.15. *Dusting*: The development of a powdered material at the surface of hardened concrete (see Fig. A.2.15).

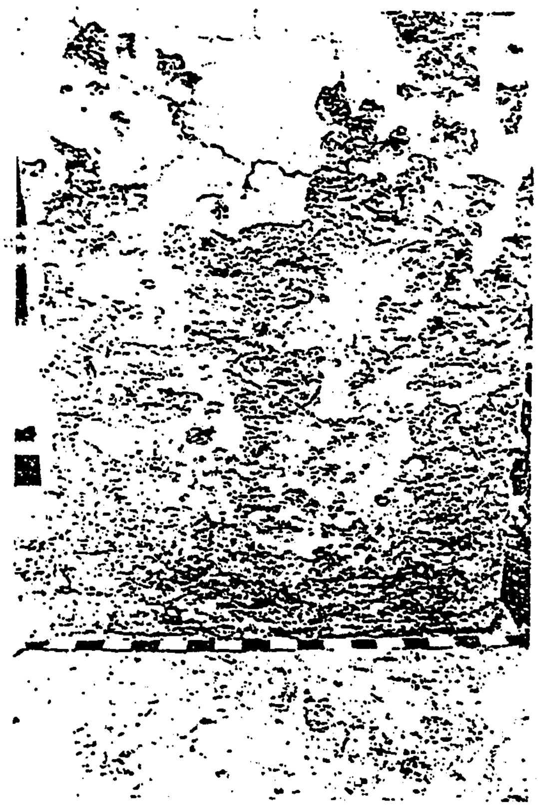


Fig. A.2.9.3.a—Scaling (medium)

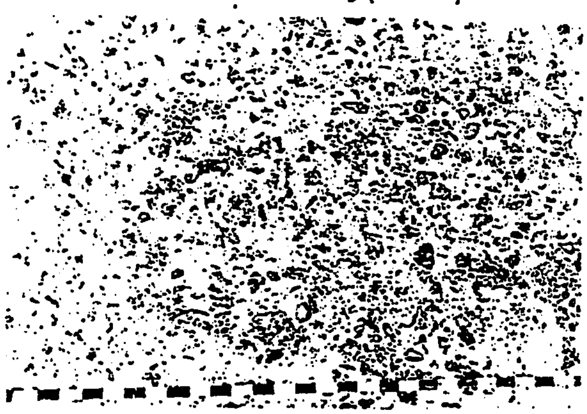


Fig. A.2.9.3.b—Close-up of scaling (medium)

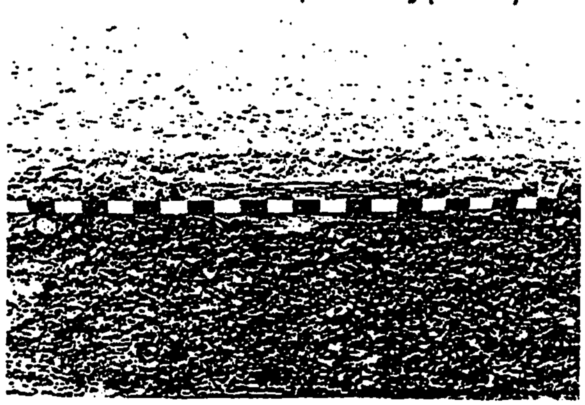


Fig. A.2.9.4.a—Close-up of scaling (severe)

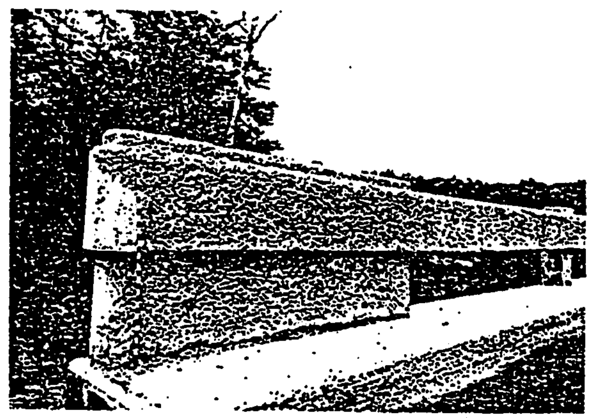


Fig. A.2.9.4.b—Scaling severe

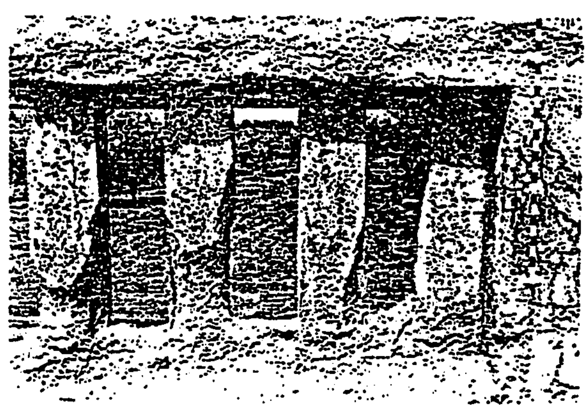


Fig. A.2.9.5.a—Scaling (very severe)

Fig. A.2.9.5.b—Close-up of scaling (very severe)

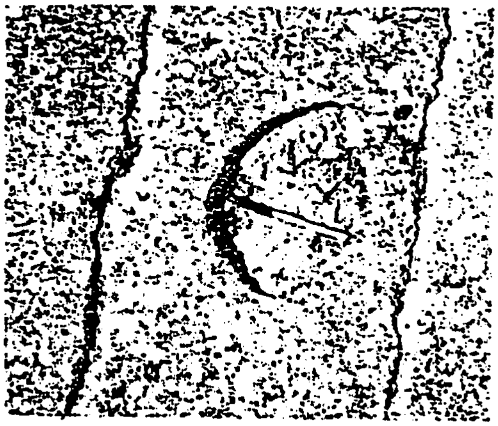


Fig. A.2.10.1—Small spall

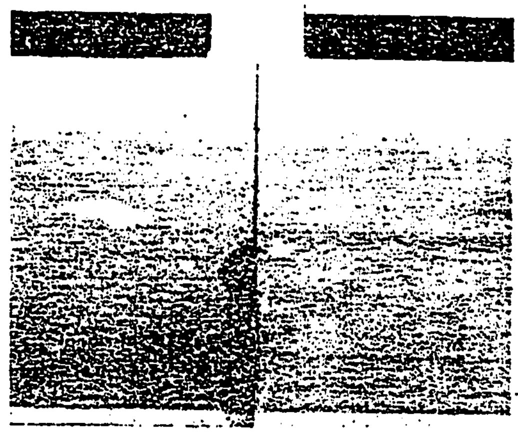


Fig. A.2.11.a—Joint spall

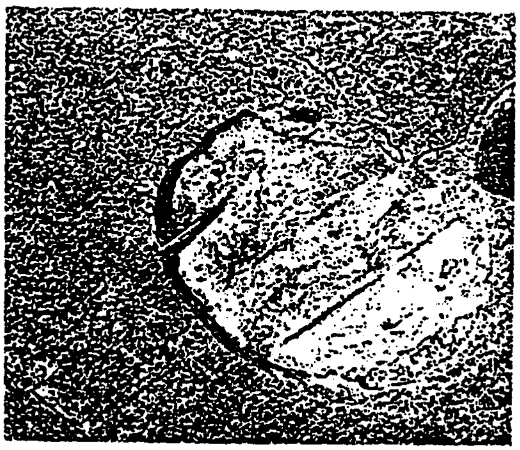


Fig. A.2.10.2—Large spall

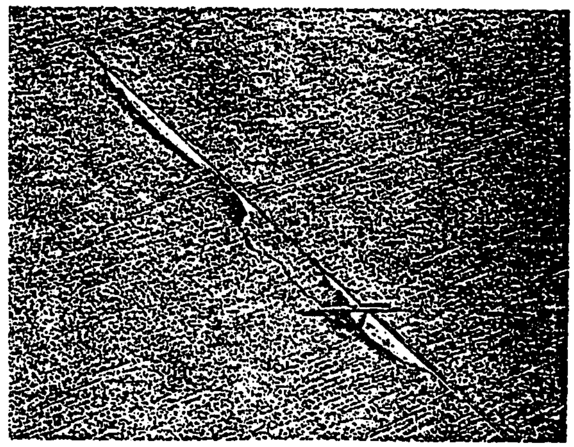


Fig. A.2.11.b—Joint spall

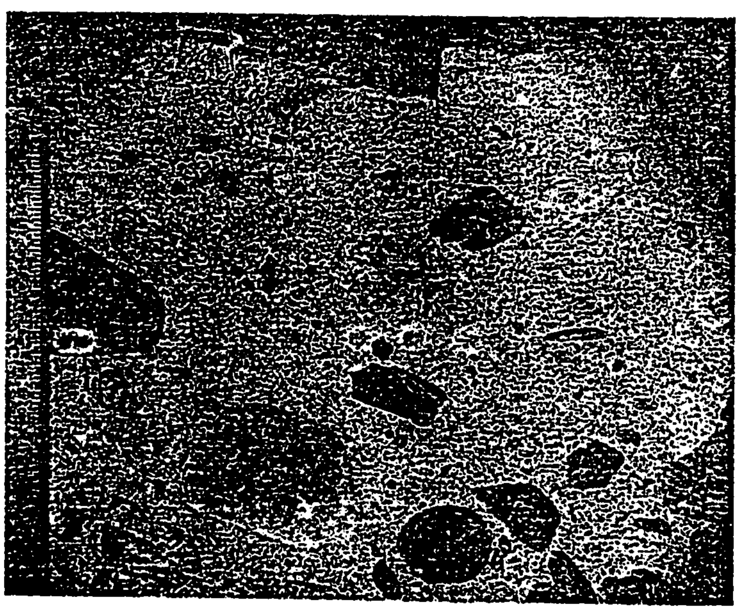


Fig. A.2.15—Dusting; surface at top of ruler is a floor surface of concrete placed very wet and which also carbonated; segregation is also evident

A.2.16. *Corrosion*: Disintegration or deterior- of concrete or reinforcement by electrolysis · chemical attack (see Fig. A.2.16).

I. Textural defects:

A.3.1. *Bleeding channels*: Essentially verti- ocalized open channels caused by heavy ing (see Fig. A.3.1).

A.3.2. *Sand Streak*: Streak in surface of ed concrete caused by bleeding (see Fig.).

A.3.3. *Water pocket*: Voids along the under- of aggregate particles or reinforcing steel n formed during the bleeding period. Ini- filled with bleeding water.

A.3.4. *Stratification*: The separation of over-wet or overvibrated concrete into horizontal layers with increasingly lighter material toward the top; water, laitance, mortar, and coarse aggregate will tend to occupy successively lower positions in that order; a layered structure in concrete resulting from placing of successive batches that differ in appearance (see Fig. A.3.4.).

A.3.5. *Honeycomb*: Voids left in concrete due to failure of the mortar to effectively fill the spaces among coarse aggregate particles (see Fig. A.3.5.a and A.3.5.b).

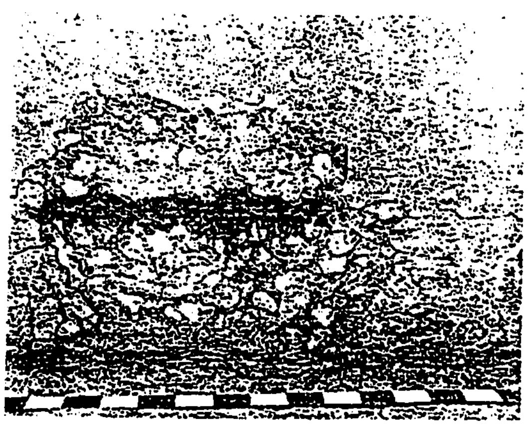


Fig. A.2.16—Corrosion

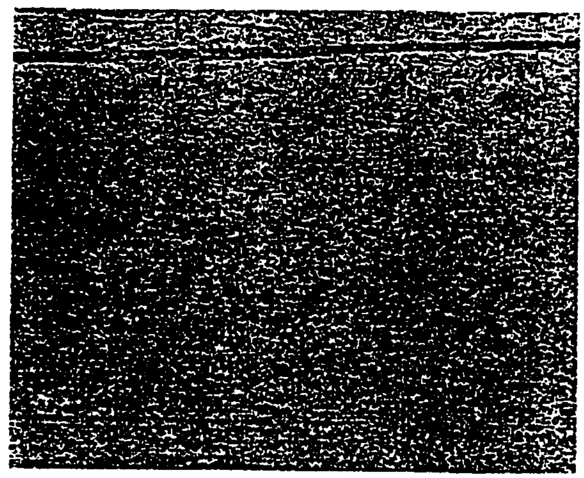


Fig. A.3.2—Sand streaking on a vertical formed surface

A.3.1—Bleeding channels and water pockets of con- in a caisson; note laitance below particles of coarse aggregate

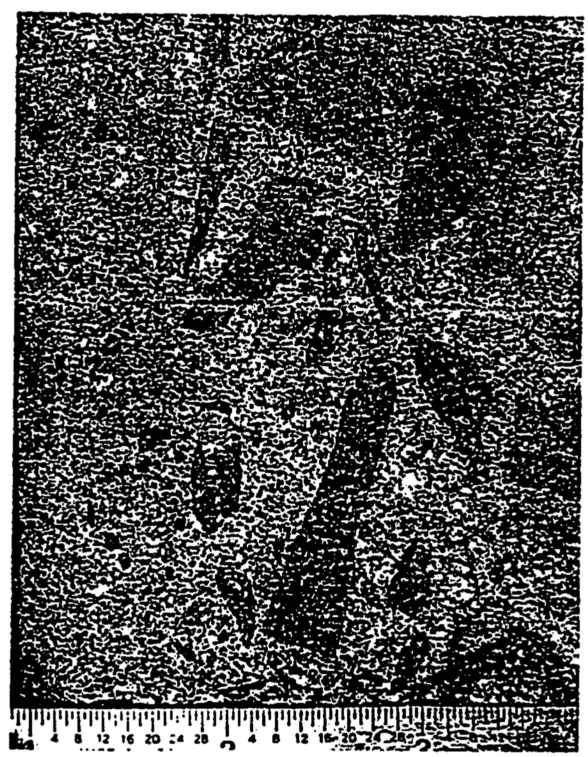


Fig. A.3.4—Stratification

Fig. A.3.5.a—Honeycomb

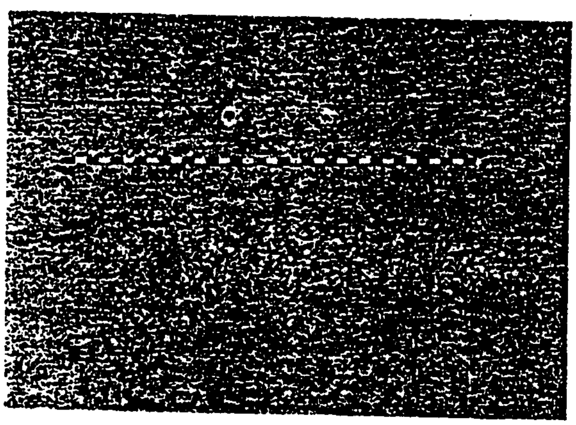


Fig. A.3.5.b—Honeycomb

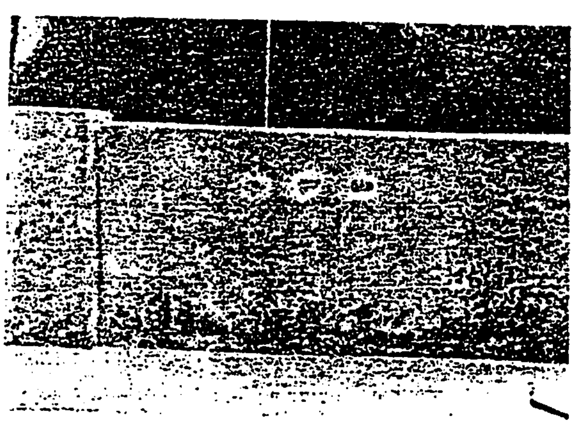


Fig. A.3.8—Discoloration

A.3.6. *Sand Pocket*: Part of concrete containing sand without cement.

A.3.7. *Segregation*: The differential concentration of the components of mixed concrete, resulting in non uniform proportions in the mass.

A.3.8. *Discoloration*: Departure of color from that which is normal or desired (see Fig. A.3.8).

REFERENCES

1. ACI Committee 116, "Cement and Concrete Terminology"—ACI 116R-78, American Concrete Institute, Detroit, 1978, 50 pp., Also, *ACI Manual of Concrete Practice*, Part 1.
2. Committee DB-5, "Standard Nomenclature and Definitions for Use in Pavement Inspection and Maintenance," Highway Research Board, Washington, D.C.
3. *Trilingual Dictionary of Engineering Materials Testing*, RILEM Bulletins 20-25, Paris, 1955.

This report was approved by letter ballot of the committee and reported to ACI headquarters Jan. 5, 1967. At the time of balloting (late 1966), the committee consisted of 22 members, of whom 19 voted affirmatively, 1 negatively, one "conditionally" affirmative, and one not returning his ballot.

Guide for Concrete Inspection*

Reported by ACI Committee 311

This guide sets forth procedures relating to concrete construction which will serve as a guide to owners, architects, and engineers in planning their inspection program. The need for adequate inspection as a requirement for high quality, attractive appearing concrete at the least cost is emphasized.

Keywords: aggregates; air entrained concretes; architectural concrete; cast-in-place pipes; cast stone; cements; cold weather construction; concrete construction; concrete finishing (fresh concrete); control charts; conveying; curing; excavation; failure; formwork (construction); foundations; hot weather construction; **inspection**; lightweight concretes; masonry; mass concrete; **mix proportioning**; mixing; preplaced aggregate concrete; pressure grouting; prestressed concrete; protective coatings; **quality control**; reinforced concrete; reinforcing steels; shotcrete; **standards**; structural design; terrazzo; **tests**; tilt-up construction; vacuum treated concrete.

THIS GUIDE IS CONCERNED only with the organization and conduct of concrete inspection. It is prepared to guide owners, architects, and engineers in the development of effective inspection organizations and programs and in the selection of procedures for carrying out adequate inspection by or on behalf of the owner for the acceptance of concrete works and for those aspects of quality assurance which are his direct concern. The guide does not cover the equally important subject of quality control, which is the inspection and testing that the contractor may require to achieve a product of the specified quality. Neither does it cover those projects where the acceptance inspection is carried out by the contractor, either because applicable regulations require it (e.g., nuclear containment vessels) or because the owner desires this procedure. In that case, many of the technical procedures shown herein apply. However, the procedural relationships will differ from those shown herein.

The recommendations are based on practices that have been proved by experience to be practicable and effective in reducing failures, preventing mistakes, and improving adherence to specifications. Adequate inspection of concrete construction permits use of advanced design procedures and specifications and frequently will expedite construction and reduce the cost of the work. Moreover, it is expected to reduce maintenance costs. All contractual and technical job relationships are outside the scope of this guide; such relationships should be defined in the contract documents.

Just as the inspection provided on behalf of the owner as part of the quality-assurance effort benefits him, so does the inspection effort provided by the contractor as part of his quality-control program benefit the contractor. Normally the required average strength is lower when the job is properly inspected; thus less cement is required for the same design strength. When a contractor furnishes concrete on a specified cement content basis, inspection efforts to maintain air content uniform benefit the contractor, because the yield is low whenever the air content is low. In precast work, inspection to maintain dimensional tolerances results in less expense later in fitting the precast units into the building.

*This report replaces "Recommended Practice for Concrete Inspection (ACI 311-75)," which has been withdrawn. Discussion of ACI 311.4R-80 appeared in *Concrete International: Design & Construction*, April 1981, Vol. 3, No. 4.

Then again, reduction in errors or variation in slump or air content of lightweight concrete due to inspection is advantageous to the contactor in providing a more trouble-free placing operation, especially when finishing is involved. Inspection tends to prevent costly errors and often reveals opportunity for money-saving changes as the job progresses.

GENERAL REQUIREMENTS

For the protection of the owner and the public, the responsibility for inspection should be vested in the architect or engineer as a continuing function of his design responsibility. The responsibility of the architect or engineer for inspection may be discharged by him directly, or through his employees, or may be delegated to an inspection agency selected by the architect or engineer. In those cases in which the owner provides his own engineering service, the owner should select the inspection agency. The fee for inspection should be a separate and distinct item and should be paid by the owner directly to the architect or engineer or to the inspection agency. Inasmuch as final responsibility for inspections rests with the architect or engineer, he should maintain close surveillance over whoever is carrying out the details of inspection for him. At no time should acceptance inspection or testing be made a function of the construction contractor, except when required by law or applicable regulations or when the owner considers that his interest is best served by such an arrangement. Furthermore, as a professional service, the selection of inspection services should be based on qualifications.

RECOMMENDED PROCEDURES

The following factors and procedures have been found over the years and on a large variety of projects to be worthwhile, and to enhance the probability of carrying out the intent of the designs and specifications. This results in a completed facility that will properly serve the purpose for which it is intended, at minimum maintenance cost. More details will be found in the *ACI Manual of Concrete Inspection*, which should, together with other ACI standards, be used to guide all personnel engaged in inspection.

1. The purpose of inspection is to assure that good practices are followed in constructing the project in accordance with the plans and specifications, and not to establish these practices. Any needed changes in plans or specifications should be brought to the attention of the architect or engineer so that the designer will have an opportunity to make the final decisions insofar as the changes affect his designs. Inspection does not relieve the contractor of his responsibility to do the work properly in accordance with the contract documents. Neither, where avoidable, should inspection interfere with the contractor's performance of the work in accordance with the contract documents. Inspection personnel should cooperate with the contractor, but must refrain from running the job for the contractor, as this is not part of the inspection function and may result in undesirable claims in case of later trouble.

2. Since the architect or engineer has final responsibility for inspection in this guide, the owner should give him the means to go with this responsibility. The architect or engineer should plan inspection commensurate with the character, magnitude, and importance of the job, and advise the owner of the approximate cost.

3. Proper inspection provides for continual inspection during the placing of concrete and its finishing, and includes preparations prior to the start of concreting such as proper formwork, placing of reinforcing, etc., as well as proper protection and curing of the finished concrete. On large projects, or where special concrete, strength, density, or texture is desired, continuous inspection of batching and mixing operations should be provided.

4. The architect or engineer should see to it that qualified and conscientious inspectors are on the job, as this is vital to effective inspection. Where such inspectors are not available or where there are special requirements in the designs and specifications, training should be carried out to qualify such inspectors.

5. A meeting between the architect or engineer, the contractor, and the inspection personnel just before construction is started is most valuable. At such a meeting questions can be answered and procedures reviewed, so that everyone knows ahead of time what is expected and how it is to be carried out. Very important among the items to be reviewed is the procedure to be followed by the inspector when he finds noncompliance with contract requirements. This advance understanding will minimize future arguments, and will give the inspector status and knowledge of the backing he can expect as well as confidence that he will receive it.

6. The following constitute a partial list of inspection functions that should be considered.

(a) Inspection and verification of batching and mixing facilities

(b) Verify proportioning of concrete mixes

(c) Inspection at batching plant

(d) Inspection, testing, and verification of materials

(e) Inspection of forms, reinforcing steel, shoring, bracing, embedded items, joints, etc.

(f) Inspection of concrete handling and placing equipment, such as buckets, chutes, buggies, hoppers, vibrators, pumps, etc.

(g) Inspection of concrete handling, placing, consolidation, finishing, curing, protection, and repair or patching

(h) Inspection at the plant of precast items, including prestressed work, for strength, dimensions, and special properties

(i) Inspection of stripping, form removal, and shoring

(j) Preparation and testing of concrete strength specimens

(k) Daily reports on all these items

7. The number of inspectors to carry out such a program will vary from job to job (depending on size, importance, contractor's setup, etc.) and must be planned by the architect or engineer for each individual case.

Items for attention under these inspection functions will be found in Appendix A.

8. Unless otherwise provided in the specifications, concrete inspected in accordance with the provisions of this guide, should have the average of all sets of three consecutive strength tests equal or exceed the required f_c' and no individual strength test result (average of two cylinders) should fall below the required f_c' by more than 500 psi (in accordance with ACI 318-83, Section 4.7.2.3).*

The *ACI Manual of Concrete Inspection* is also pertinent to the subject of inspection.

APPENDIX A

For convenient reference, in this section are listed the various items which might be covered by inspection. The list is intended as a reference, not for daily use. For a particular job, the inspector will find it necessary to have at hand a similar list containing only those items that apply to the given specifications, organizations, and job conditions. Detailed information regarding the items is contained in the text of the *ACI Manual of Concrete Inspection.*

Preliminary

Study of plans and specifications; building codes
Division of duties between engineer's representatives
Permissible tolerances of measurement
Provision for records and reports
Contractor's plant, calibrations, equipment, organization, and methods
Rights of way; interference with utilities of adjoining property

Proportioning

Test of aggregates
Proportioning of mix
Mix computations
  Grading of mixed aggregates; batch quantities; yield; air content

Materials

General (applies to all materials)
  Identification; quantities (used, on hand); acceptability; uniformity; storage conditions; handling methods; waste; schedule of testing
Cement and pozzolan
  Sampling for laboratory test
  Protection from dampness
Water potability
Aggregates
  Acceptability tests
    Gradation; organic matter; deleterious undesirable substances; soundness; resistance to abrasion; other tests
  Control tests
    Moisture; absorption; specific gravity; unit weight; voids
Admixtures
Reinforcing steel
  Size; bending; surface condition
Accessories
Fixtures
Other materials

Before concreting

Lines and grades
Excavation; foundations
  Location, dimensions, shape; drainage; preparation of surfaces

Forms

Specified type of form
Location
Alignment; provision for settlement
Stability (bearing; shores; ties and spacers)
Inspection openings
Preparation of surfaces
Final clean-up

Reinforcement in place

Size (diameter; length; bends; end anchorage)
Location (number of bars; minimum clear spacing; minimum coverage)
Splicing
Stability (wiring; chairs and spacers)
Cleanness (no loose rust; no oil, paint, dried mortar, etc.)
Fixtures (location; stability; cleanness)
Openings not shown on plans
Calibration of batching devices
Condition of mixer; speed of operation
Provision for continuous placement
Provision for curing
Provision for protection against sun, rain, hot or cold weather
Adequate tools and men for compaction, finishing, and curing

Concreting

Working conditions
  Weather; preparations completed; specified interval since previous placement; lighting for night work; covering and protection
Batching
  Cement; pozzolan; aggregates; water; admixtures
  Check batching devices
  Check yield of concrete

*Since ACI 318 is subject to periodic revision, the reader should check the current requirements and conform to them.

Mixing
Minimum time; batches delayed in mixer; maximum time; over-loading; number of revolutions of drum; water used; mixing capacity of drum; amount of concrete
Control of consistency
Observation of concrete being placed; tests; adjustments of water or admixtures in mix
Monitoring of air content
Concrete temperature check (if required)
Conveying
No segregation of materials; no excessive stiffening or drying out; time limits
Placing
Uniform and dense concrete; continuous operation; preparation of contact surfaces; mortar bedding; vertical drop, no dropping against forms or reinforcement; little or no flow after depositing; depth of layers; water gain; rock pockets; removal of temporary ties and spacers; disposition of rejected batches; placing concrete under water
Contraction joints
Location
Forming or tooling
Dowels or ties (if any) in place and aligned
Construction and hinge joints
Location; preparation of surface
Dowels or ties (if any) in place and aligned
Expansion and isolation joints
Joint filler material; location; alignment; stability; freedom from interference with subsequent movement
Finishing of unformed surfaces
Shallow surface layer of mortar; water gain; no overworking; first floating; alignment of surface; final hard troweling; plastic shrinkage cracks; rain
Finishing of formed surfaces
Condition of surfaces upon removal of forms (honeycomb, peeling, ragged tie holes, ragged form lines); repair of defects; surface treatment; no surface drying
Schedule of testing

After concreting
Protection from damage
Impact; overloading; marring of surfaces
Time of removal of forms
Curing
Surfaces continuously moist; time of beginning curing; length of curing period; see also concreting in cold and hot weather
Joints
Clean, and seal
Timing and alignment of sawn joints

Tests of concrete
Consistency tests
Tests for air content
Test for unit weight of fresh concrete
Analysis of proportions of fresh concrete
Strength tests
Molding specimens; curing specimens (standard conditions, field conditions); field tests; shipping specimens to laboratory
Tests of hardened concrete
Cores
Impact hammer; probe
Pull-out
Other tests

Records and reports
Records: materials; mix computations; batching and mixing; placing and curing; special
Reports: daily; summary
Diary
Photographs

SPECIAL WORK

Cold-weather concreting
Limiting temperatures and times
Outdoor air; enclosure; materials; concrete
Heating materials, contact surfaces, and enclosure; protection from drying, carbonation, and carbon monoxide
Tight enclosure or insulated forms
Removal of forms; protection from too rapid cooling

Hot-weather concreting
Cooling materials, prewetting aggregates and contact surfaces; protecting concrete
Limiting combinations of wind, relative humidity, and ambient temperature

Filling under base plates
Preparation of base; proper mix; complete filling of voids

Pressure grouting
Holes (depth, spacing, freedom from clogging)
Materials (acceptability, quantities used)
Injection (sequence, pressure, times, completeness of penetration, no damage to structure)

Shotcrete
Materials (acceptability, quantities); condition of equipment; preliminary mixing; pressures (air, water); preparation of surfaces; application (thickness, no sagging, construction joints); surface finish; curing; tests

Two-course floors
Preparation of surface of base course; materials; proportions and consistency; uniform screeding; rolling or tamping; first floating; final troweling; curing

Terrazzo
Thickness of layers; uniformity; curing; dividing strips

Stucco
Mortar; preparation of backing surface; bonding to backing surface; uniform finish; curing each layer

Masonry

Units

Laboratory tests for strength and absorption

Field inspection for size, shape, and soundness

Construction

Moisture content of units; completeness of bedding in mortar; alignment; compliance with building code (mortar, minimum wall thickness, lateral support, bonding courses, supports for beams, opening in walls)

Cast stone

Laboratory tests for strength and absorption

Field inspection for soundness and uniformity (match sample)

Architectural concrete

Location and neat joining of molds; surface coating to avoid sticking or staining; curing

Reinforcement near surface; support location and material

Vibrating to minimize bugholes

Color and texture; mockup

Protection against drip stains

Surface repair; hole filling

Colored concrete

Pigments; matching of colors; thorough and intimate mixing of color with cement; uniform application and troweling; curing

Painting

Cleaning surface; neutralizing surface (if needed); uniform application; curing portland cement paints

Lightweight concrete

Lightweight aggregates (acceptability, prewetting, preventing segregation)

Cellular concrete (admixtures, timing of operations, mixing processes, foaming agents)

Test for unit weight

Mass concrete

Times and rates of placement; avoidance of high or nonuniform temperatures; bonding of lifts; prevention of aggregate breakage

Preplaced-aggregate concrete

Gradation and placement of coarse aggregate; contamination prior to grouting; void content; composition and consistency of grout; sequence and pressures of grouting; completeness of filling of voids; condition of equipment

Air-entrained concrete

Accurate measurement of air-entraining agent; tests for air content of concrete; regulation of air content; adjustment of mix to compensate for air content; avoidance of excessive mixing or vibration; avoidance of wet consistency; finishing

Tilt-up construction

Surface of casting platform; joints in sheet bondbreakers; timing and uniformity of liquid bondbreakers; alignment of edge forms; compaction of concrete at bottom corners; connections to columns; provision for expansion, if specified; strength of concrete at time of lifting; pick-up points; avoidance of excessive pulling, jerking, or jarring

Underwater construction

Avoidance of flowing water; temperatures; continuous placement; operation of tremie or bucket; minimizing of wash; protection from flowing water for several days

Vacuum concrete

Final thickness of slabs; timing and duration of application of vacuum; uniformity of processing; condition of mats

Prestressed concrete

Strength of concrete at time of prestressing; sheathing of reinforcement, if specified; accurate placing of reinforcement; avoidance of obstruction or excessive friction; measurement of tension by means of jack pressure and/or lengthening of steel; thoroughness of grouting, if specified

This report was submitted to ballot of the committee which consists of 18 members; 16 members returned affirmative ballots, and 2 ballots were not returned. It has been processed in accordance with Institute procedure and is approved for publication.

ACI Committee 311

Inspection of Concrete

Bertold E. Weinberg, Chairman — Claude E. Jaycox, Secretary

Joseph F. Artuso, Jorge Garcia Bernardini, Luke Cosme, Edward J. Curtin, Donald E. Dixon, R. Farsky, Robert L. Henry, Frank W. Joyce, Oswin Keifer, Jr., Ralph O. Lane, Dominic C. Lavalla, Charles A. McVean, Dixon O'Brien, Jr., Herman G. Protze III, Lewis H. Tuthill, Roger E. Wilson

The committee voting on the minor revisions of 1984 was as follows:

Roger E. Wilson, Chairman — Claude E. Jaycox, Secretary

Edward A. Abdun-Nur, Joseph F. Artuso, Russell J. Burley, Donald E. Dixon, Robert L. Henry, Thomas A. Johnson, Francis W. Joyce, Oswin Keifer, Jr., Ralph O. Lane, Dominic C. Lavalla, Charles W. Mayer, Dixon O'Brien, Jr., Jay R. Prestera, Michael T. Russell, Lewis H. Tuthill, Stanley Eugene Turney, James Lee Trujillo, Bertold E. Weinberg

Appendix - A.2 Sample Inspection Report.

INSPECTION REPORT
(Al - Tayyib, 1986)

Date : ____________
Building Location : ______________________

	Sound (+)	Condition Suspected (0)	Defected (-)
BUILDING SURROUNDINGS			
Fences, Gates, and Boundary walls			
Paths, Landscapes, Paved areas			
Swimming Pools			
Car Parks, Roads, and Curbs			
Drainage			
Manholes			
EXTERNAL DECORATION			
Surfaces Paint/Stain			
Wall coating			
Other surfaces			
INTERNAL DECORATION			
Ceilings			
Walls			
Other surfaces			
MAIN STRUCTURE			
Foundations and Basements			
Footings			

- Girders ______________
- Retaining Walls ______________
- Mat Foundation ______________
- Piles ______________

Frame

- Beams ______________
- Columns ______________
- Slabs ______________

Staircases

- Structures ______________
- Treads ______________
- Finishes ______________
- Balustrade ______________
- Soffits ______________

External Walls

- Masonry/Brickwork ______________
- Cladding ______________
- Rendering ______________
- Structure ______________
- Jointing ______________

Internal Walls and Partitions

- Structure ______________
- Doors and Openings ______________
- Jointing ______________
- Finish ______________

Roofing

Flat/Pitched	______
Insulation	______
Covering	______
Waterproofing	______
Parapets	______
Gutters	______
Rainwater pipes	______

MECHANICAL INSTALLATION

Boilers, Instrumentation, and Automatic Control	______
Steam and Hot Water Distribution including Heat exchangers and Heating Appliances	______
Workshop Equipment, Lifting Appliances and Special Industrial Equipment	______
External Water Supply, Treatment and storage Plant	______
Elevators (Lifts)	______
Air Conditioning, Ventilation and Refrigeration	______
General Utilities	______

ELECTRICAL INSTALLATION

Switchgear	______
Distribution	______
Fittings and Equipments	______
Burglar Alarm	______
Smoke Detector	______

Lighting Conductor ______________________

Cathodic Protection ______________________

GAS INATALLATION

Pipes ______________________

Fittings ______________________

Equipment ______________________

PLUMPING AND SANITARY SERVICES

Cold Water Service Pipes, Storage Tanks, Cisterns, and Valves ______________________

Hot Water Service Pipes, Domestic Boilers, Valves and Insulation ______________________

Sanitary Fittings including Taps and Traps ______________________

STRUCTURAL MOVEMENT

TELLS TALES

FAILURE OF MATERIALS

DESIGN OF CONSTRUCTION DEFECTS

REMARKS

Appendix - A.3 Visual Inspection Summary

A Partial Guide for Identifying Structural Problems during Visual Examination of Reinforced Concrete Beam and Slabs (Mailvaganam, 1992)

An Example of Visual Inspection Notes

Date of Inspection:

Name of Dam: Date Built:

Sketch: Note - Sunny, Shady, Drainage Areas

Condition	Up-Stream	Down-Stream	Deck	Spillway Area
1. Surface General				
Good	☐	☐	☐	☐
Satisfactory	☐	☐	☐	☐
Poor	☐	☐	☐	☐

2. Cavitation & Erosion: Severe ☐ Minor ☐ None ☐

3. Cracks: Frequency:	Up-Stream	Down-Stream	Deck	Spillway Area
Vertical	☐	☐	☐	☐
Horizontal	☐	☐	☐	☐
Random	☐	☐	☐	☐
Size:				
Fine (<1 mm)	☐	☐	☐	☐
Medium (1 to 2 mm)	☐	☐	☐	☐
Wide (>2 mm)	☐	☐	☐	☐
Leaching:				
Localized	☐	☐	☐	☐
Extensive	☐	☐	☐	☐
4. Scaling				
Light (<5 mm)	☐	☐	☐	☐
Medium (5 to 10 mm)	☐	☐	☐	☐
Severe (>10 mm in Agg)	☐	☐	☐	☐
Extensive	☐	☐	☐	☐
Localized	☐	☐	☐	☐

Notes:

	Up-Stream	Down-Stream	Deck	Spillway Area
5. Spall				
Small	☐	☐	☐	☐
Large	☐	☐	☐	☐
At Joint	☐	☐	☐	☐
Many	☐	☐	☐	☐
A Few	☐	☐	☐	☐
6. Ravelling:				
Severe	☐	☐	☐	☐
Minor	☐	☐	☐	☐
None	☐	☐	☐	☐
Extensive	☐	☐	☐	☐
Localized	☐	☐	☐	☐
7. Previous Repair Work				
Present	☐	☐	☐	☐
None	☐	☐	☐	☐
Good	☐	☐	☐	☐
Satisfactory	☐	☐	☐	☐
Poor	☐	☐	☐	☐

8. Signs of:

- Settlement ☐
- Expansion ☐
- Contraction ☐
- Deflection ☐

Note Locations:

9. General Comments and Recommendations

For NDT and Other Tests:

TABLE .-
Cont.

EXAMPLE OF COMPONENT INSPECTION FORM

Site No. 33 - 199

Substructures

	Location	Condition*
Abutments	N/S	G/G
Ballast walls	None	
Piers	N/C/S	G/G/F
Slope paving	N/S	P/G

Remarks

Piers – Vertical cracks in E. column of S. Pier, 1 m above ground. Slippage of grouted rip-rap has resulted in blow-up at toe of north slope.

Handrails and Parapets

		Number	Condition*
Parapet walls with 1, 2 rails			
Barrier walls			
Posts	Concrete End Post	4	G
	Steel	46	F
Panels	Concrete		
	Steel	48	F
Other.			

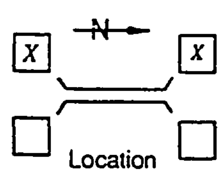
Numerous panels and posts show paint flaking and rusting. Panel near S.E. corner damaged by vehicle impact. Concrete corner posts in good condition except for rust staining at the base of the S.W. post.

Approaches

			Exposed concrete	Asphalt	Condition*
Approach slabs	Yes	X		X	G
	No				
Approach road surface				X	G

			Condition*
Curb and gutter	Yes	X	
	No		F

			Number
Catch basins	Yes	X	2
	No		



Location (show north)

Curb and gutter adjacent to catch basins only, settled approx. 40 mm.

The single cable guiderail is in very poor condition, cable slack and posts deteriorated or broken.

Beams

Type	T-beam
Number	6
Condition*	G

Rust stains from chair supports on underside of all beams. Concrete is in good condition.

* Condition – G = Good, F = Fair, P = Poor

TABLE -
Cont.

EXAMPLE OF COMPONENT INSPECTION FORM

Site No. 33 - 199

Substructures

	Location	Condition*
Abutments	*N/S*	*G/G*
Ballast walls	*None*	
Piers	*N/C/S*	*G/G/F*
Slope paving	*N/S*	*P/G*

Remarks

Piers – Vertical cracks in E. column of S. Pier, 1 m above ground. Slippage of grouted rip-rap has resulted in blow-up at toe of north slope.

Handrails and Parapets

		Number	Condition*
Parapet walls with 1, 2 rails			
Barrier walls			
Posts	Concrete End Post	*4*	*G*
	Steel	*46*	*F*
Panels	Concrete		
	Steel	*48*	*F*
Other.			

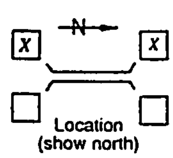
Numerous panels and posts show paint flaking and rusting. Panel near S.E. corner damaged by vehicle impact. Concrete corner posts in good condition except for rust staining at the base of the S.W. post.

Approaches

			Exposed concrete	Asphalt	Condition*
Approach slabs	Yes	*X*		*X*	*G*
	No				
Approach road surface				*X*	*G*

			Condition*
Curb and gutter	Yes	*X*	
	No		*F*

			Number
Catch basins	Yes	*X*	2
	No		



Curb and gutter adjacent to catch basins only, settled approx. 40 mm.

The single cable guiderail is in very poor condition, cable slack and posts deteriorated or broken.

Beams

Type	T-beam
Number	6
Condition*	G

Rust stains from chair supports on underside of all beams. Concrete is in good condition.

* Condition – G = Good, F = Fair, P = Poor

Appendix - A.4 Petrographic Survey Data Sheet

Ontario Hydro Research Division Petrographic Examination of Hardened Concrete

(Mailvaganam, 1992)

CEMENT MATRIX

% of total volume : % Visual estimate ☐ Point count ☐
Appearance of broken surface : Subtranslucent ☐ Dull ☐ Chalky ☐
Colour : Grey ☐ Light Grey ☐ White ☐ Brown ☐ Other -
Colour distribution : Even ☐ Mottled ☐ Gradational ☐
Bleeding : Extensive ☐ Minor ☐ Not observed ☐
Carbonation : Surficial only ☐ Along fractures ☐ Partial ☐ Total ☐
Slag cement : Observed ☐ Not observed ☐
Fly ash : Observed ☐ Not observed ☐

VOIDS

% of total volume : % Visual estimate ☐ Point count ☐
Distribution : Even ☐ Uneven ☐ Clustered ☐
Shape : Spherical ☐ Nonspherical ☐ Ellipsoidal ☐ Irregular ☐
Entrained air : Air-entrained ☐ Non-air-entrained ☐
Interior lustre : Dull ☐ Shining ☐
Interior condition : Empty ☐ Lined ☐ Partly filled ☐ Totally filled ☐
% Voids with mineralization : Most ☐ About half ☐ Few ☐ None ☐
Mineralization : Alkali-silica gel ☐ Ettringite ☐ Portlandite ☐ Calcium carbonate ☐

CRACKS

Amount : Extensive ☐ Occasional ☐ None ☐
Continuity and Distribution:

Orientation : Vertical ☐ Horizontal ☐ Random ☐
Location : Through aggregate particles ☐ Around aggregate particles ☐
Width (mm) : Range to Average
% filled : %
Filling material : Alkali-silica gel ☐ Ettringite ☐ Portlandite ☐
Calcium carbonate ☐ Other -
Associated with embedded items : Yes ☐ No ☐

EMBEDDED ITEMS Yes ☐ No ☐

Description :
Condition : Clean ☐ Corroded ☐ Decayed ☐
Size (mm) :
Location / Orientation :
Other :

GENERAL COMMENTS

Approved by : Submitted by :
Distribution :

Report No :

ntin

TABLE
Cont.

ONTARIO HYDRO RESEARCH DIVISION
PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE

Project :
Region :
Area :
Structure :

Job No. :
File No. :
Report No. :
Date Issued :

Sample Type : Core ☐ Cylinder ☐ Chunk ☐

Sample Description :

Sample Preparation : Freshly broken surface ☐ Weathered surface ☐ Polished face ☐ Thin Section ☐ No.

CONCRETE

Hit with hammer : Ring ☐ Dull ☐

Break with fingers : Particles not dislodged ☐ Powdery ☐ Friable ☐

During sawing : Clean cut ☐ Breaks easily ☐

Cement / coarse aggregate bond : Good ☐ Partial ☐ Poor ☐

Cement / fine aggregate bond : Good ☐ Partial ☐ Poor ☐

Presence of honeycombing : Not observed ☐ Minor ☐ Extensive ☐

COARSE AGGREGATE

Source :

% of total volume : % Visual estimate ☐ Point count ☐

Material type : Gravel ☐ Quarried ☐ Mixture ☐ Other -

Shape : Rounded ☐ Partly crushed ☐ 100 % Crushed ☐

Distribution : Even ☐ Uneven ☐ Chaotic ☐

Nominal size : (mm)

Maximum size : (mm)

Preferred orientation : Present ☐ Not observed ☐

LITHOLOGICAL TYPE	% OF COARSE AGGREGATE	REACTION RIMS / GEL / FRACTURES	REMARKS

FINE AGGREGATE

Source :

% of total volume : % Visual estimate ☐ Point count ☐

Material type : Natural ☐ Manufactured ☐ Mixture ☐ Other -

Shape : Rounded ☐ Subrounded ☐ Subangular ☐ Angular ☐

Distribution : Even ☐ Uneven ☐ Chaotic ☐

Preferred orientation : Present ☐ Not observed ☐

cont.

Appendix - B Defect Plates

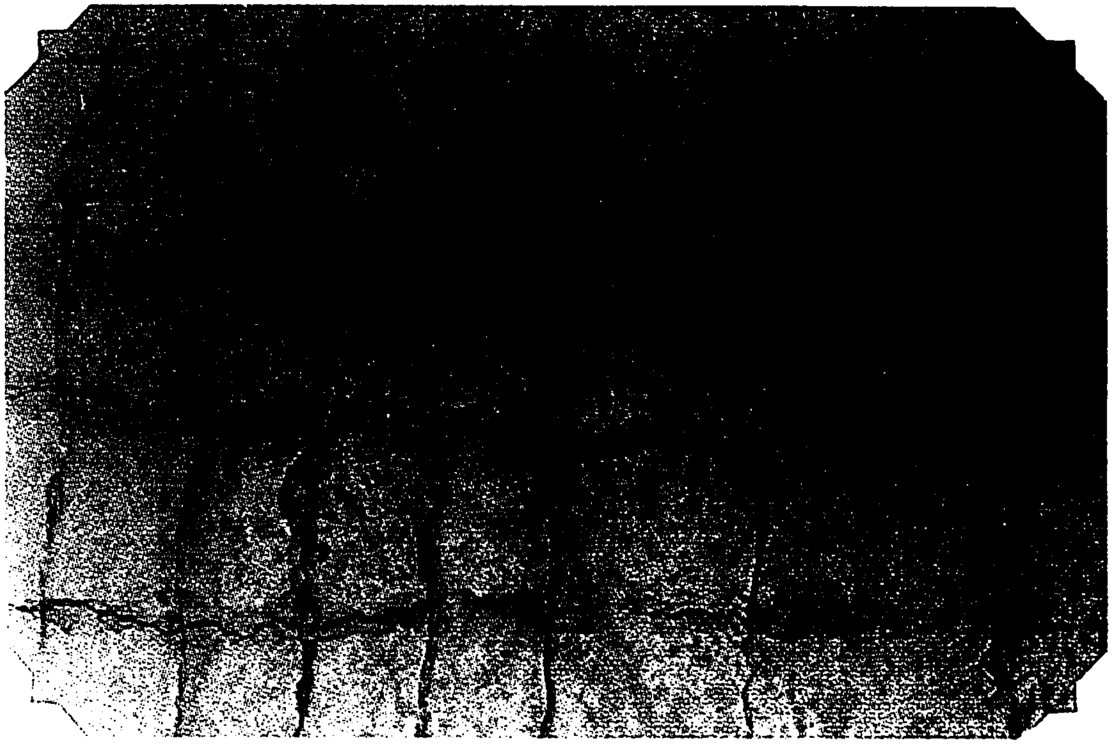


Plate B-1 Shrinkage cracks following reinforcement direction.

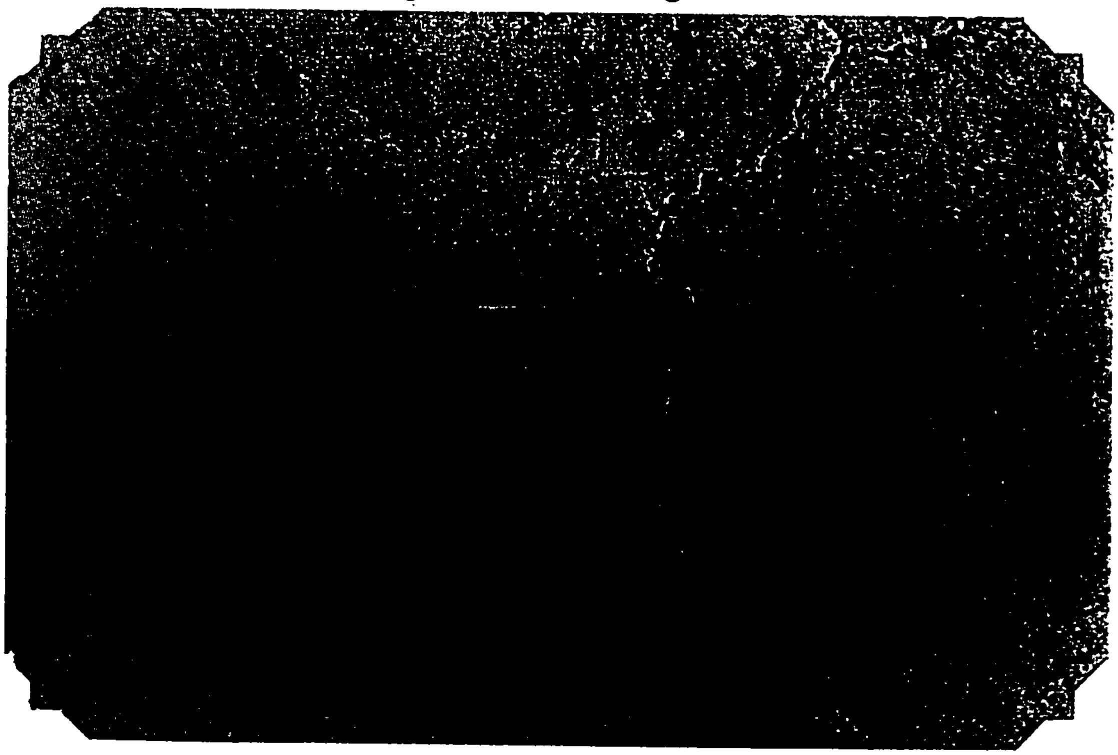


Plate B-2 Random pattern shrinkage cracks.

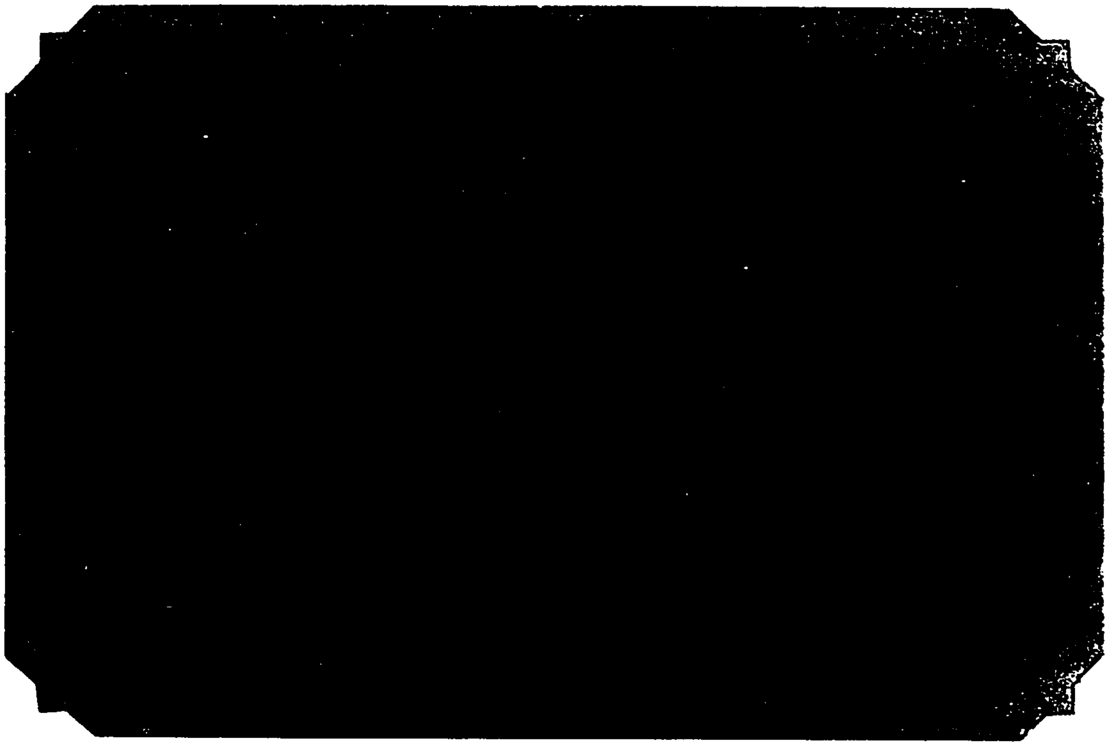


Plate B-3 Drying shrinkage cracks.

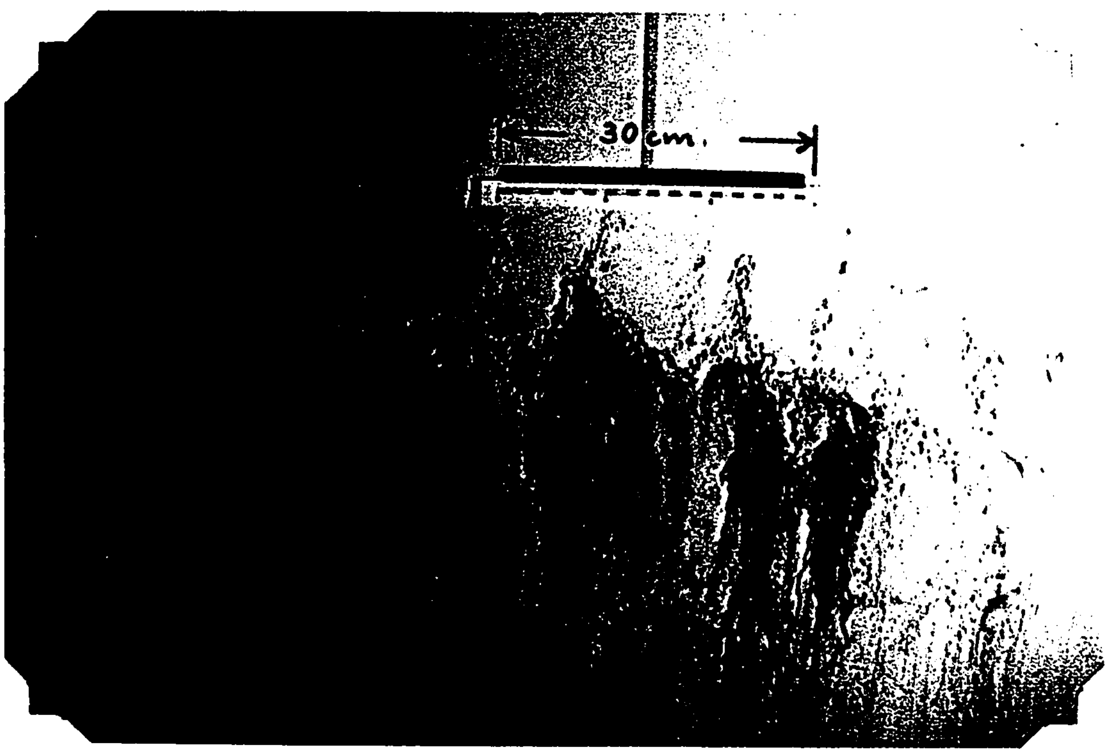


Plate B-4 Early thermal cracks at building basement.

Plate B-5 Bottom of concrete slab, spalling and corrossion due to contamination of aggregates with chlorides and sulphates.

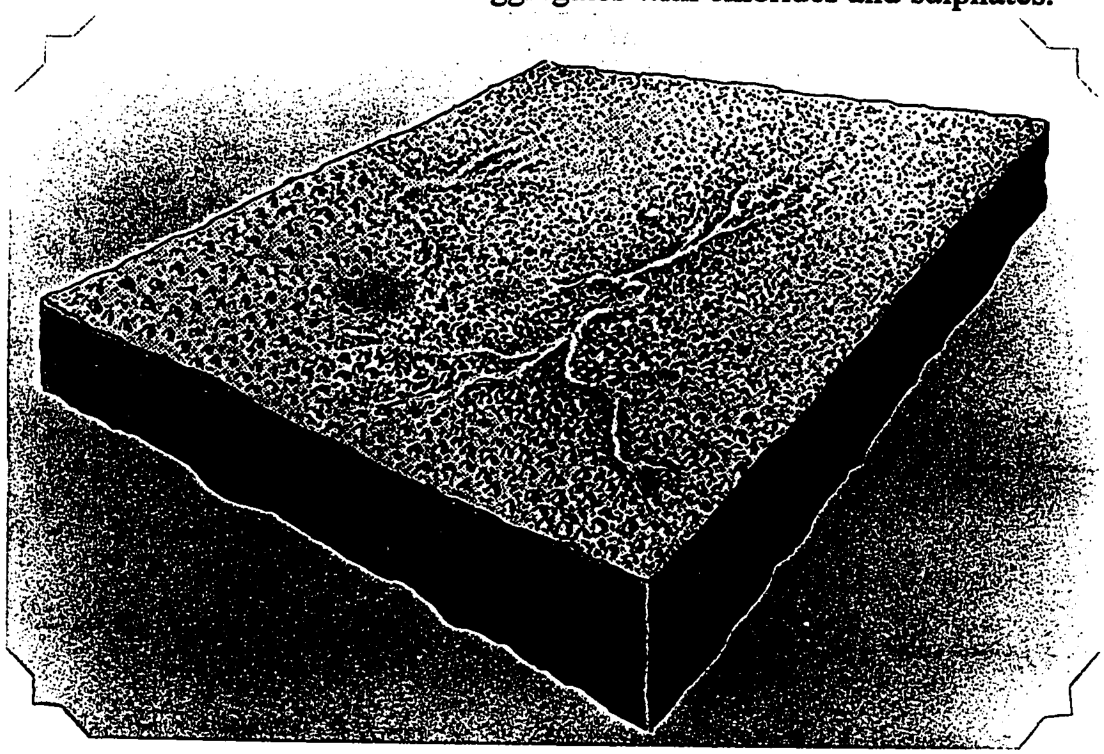


Plate B-6 Representation of alkali-aggregate reaction manifestation.

Plate B-7 Poor concrete quality due to execess water and poor compaction.

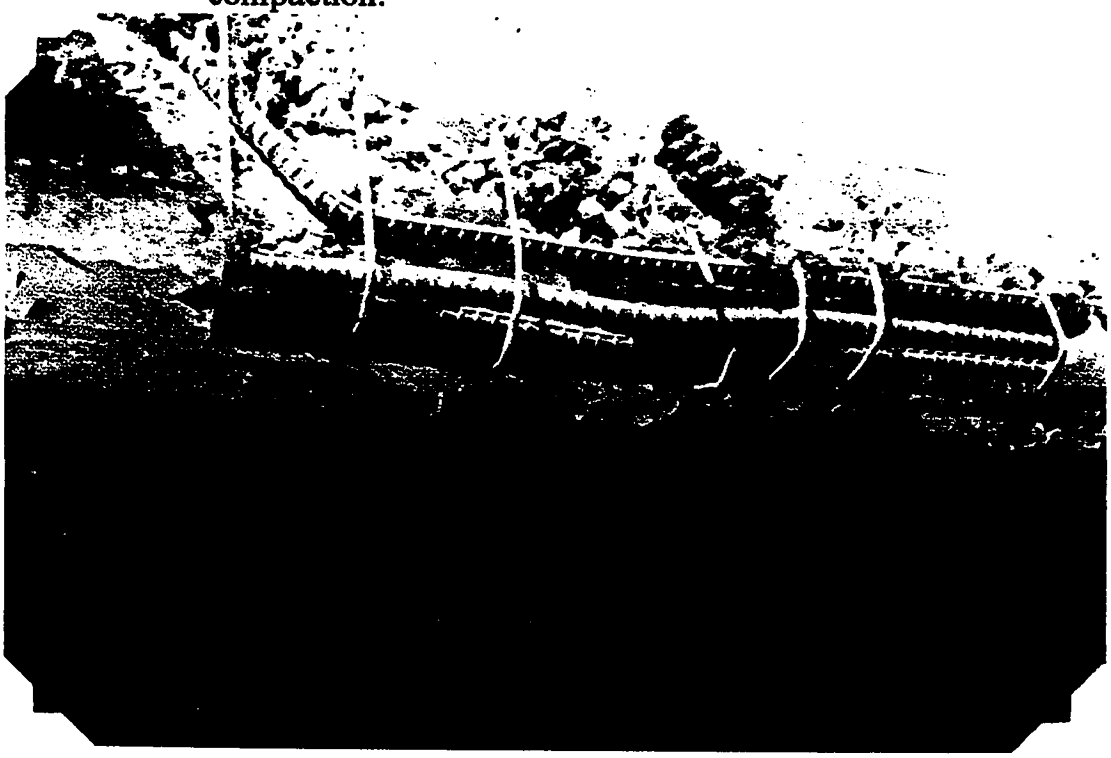


Plate B-8 Low water content concrete.

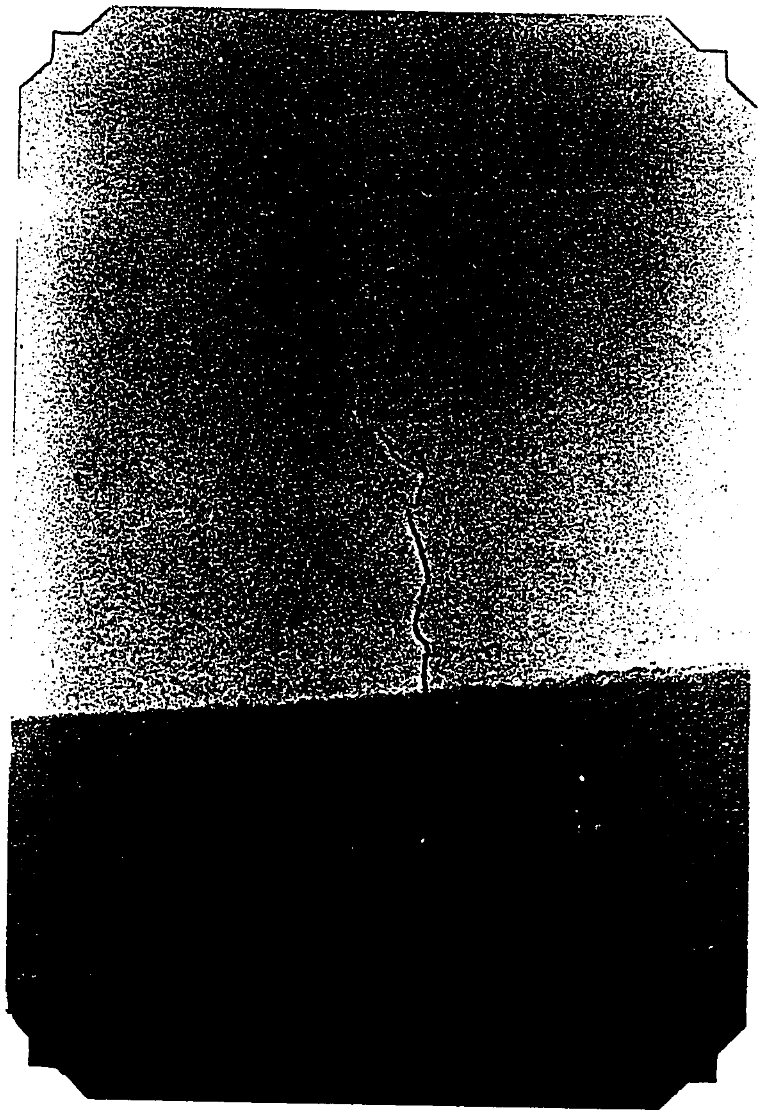


Plate B-9   Middle of beam flexural crack.

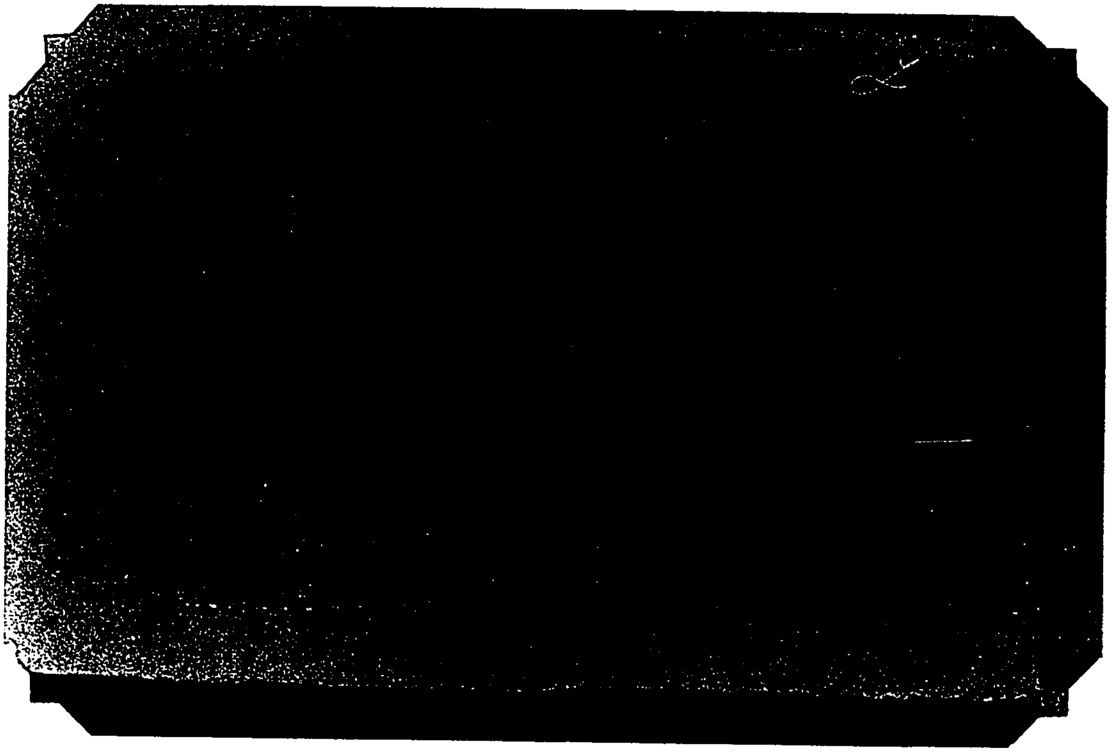


Plate B-10 Near support shear crack.

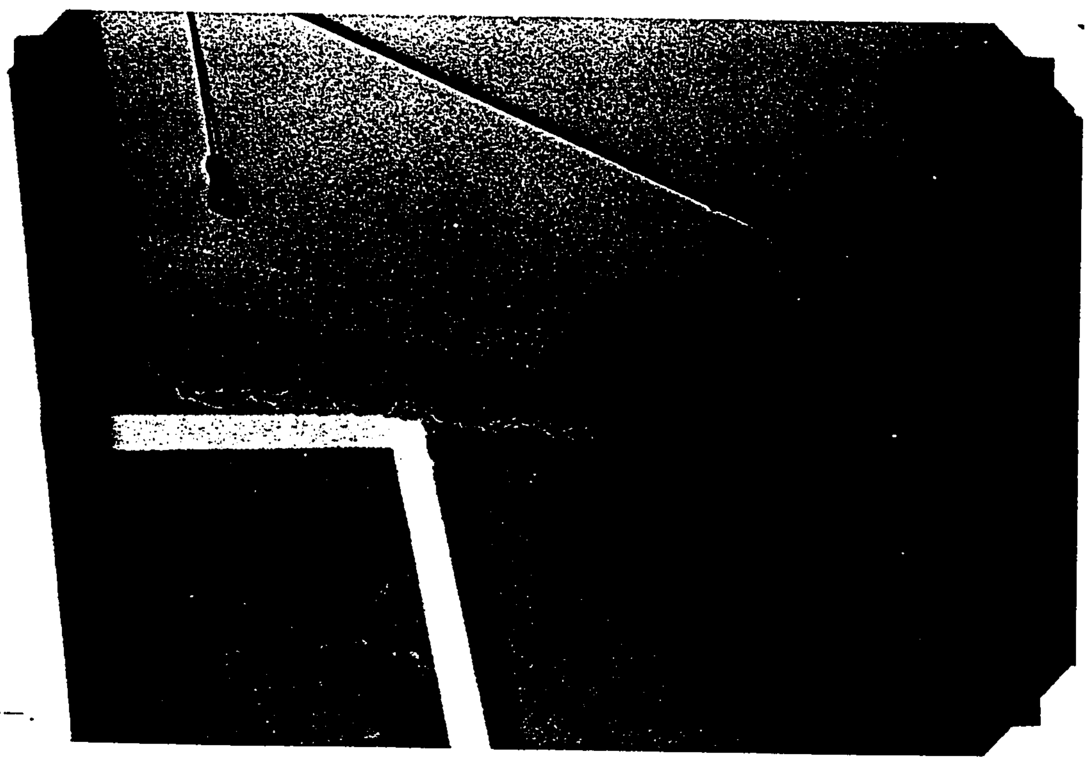


Plate B-11 Settlement cracks at walls between beams and block walls.

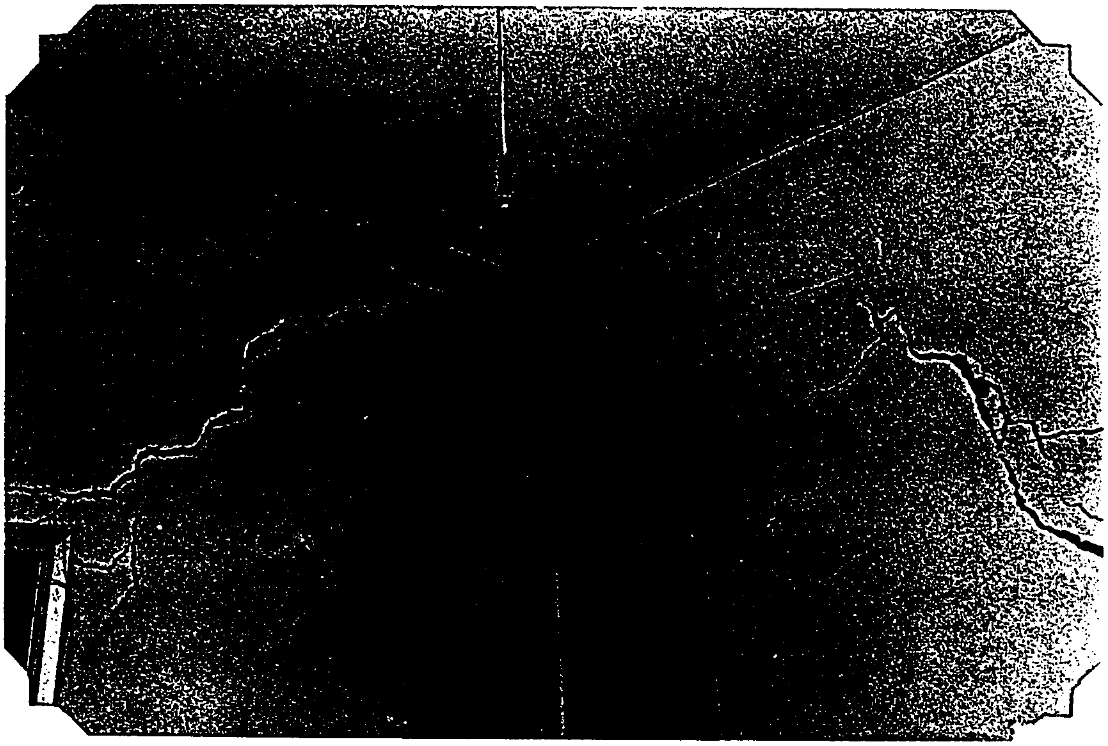


Plate B-12 Differential settlement cracks at partition walls

Plate B-13 Column deterioration due to use of water containing sulphates.

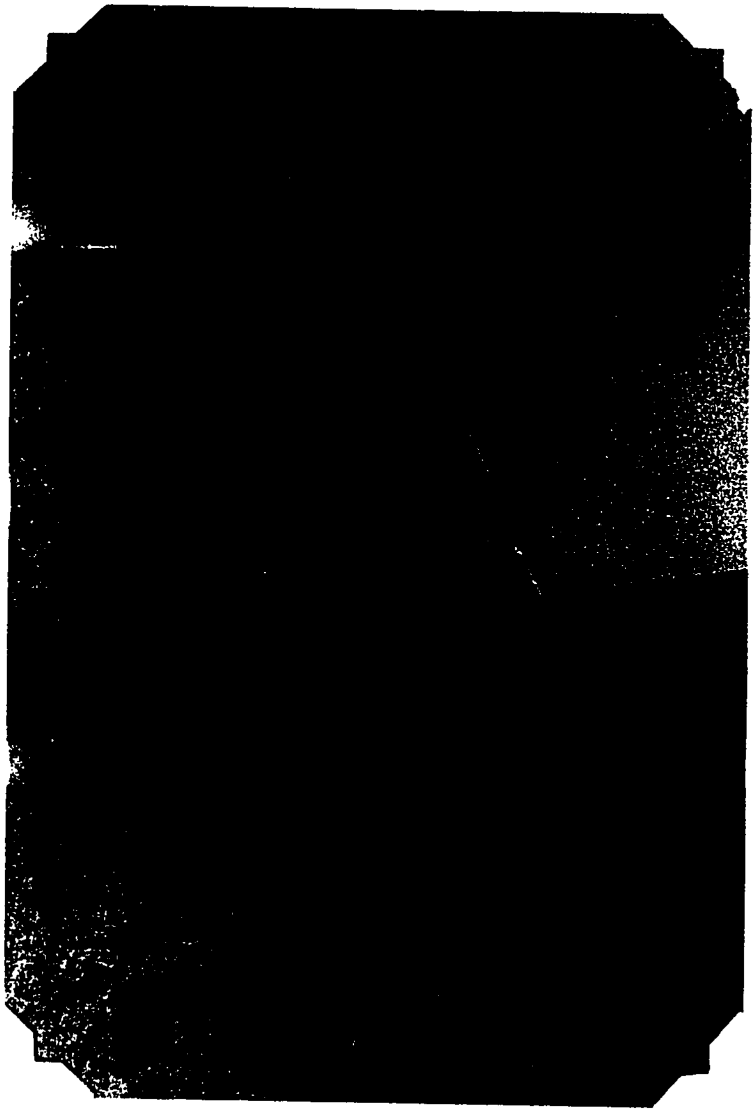


Plate B-14 Column buckling due to lack of lateral reinforcement near column top.

Plate B-15 Concrete deterioration due to presence of chlorides and sulphates.

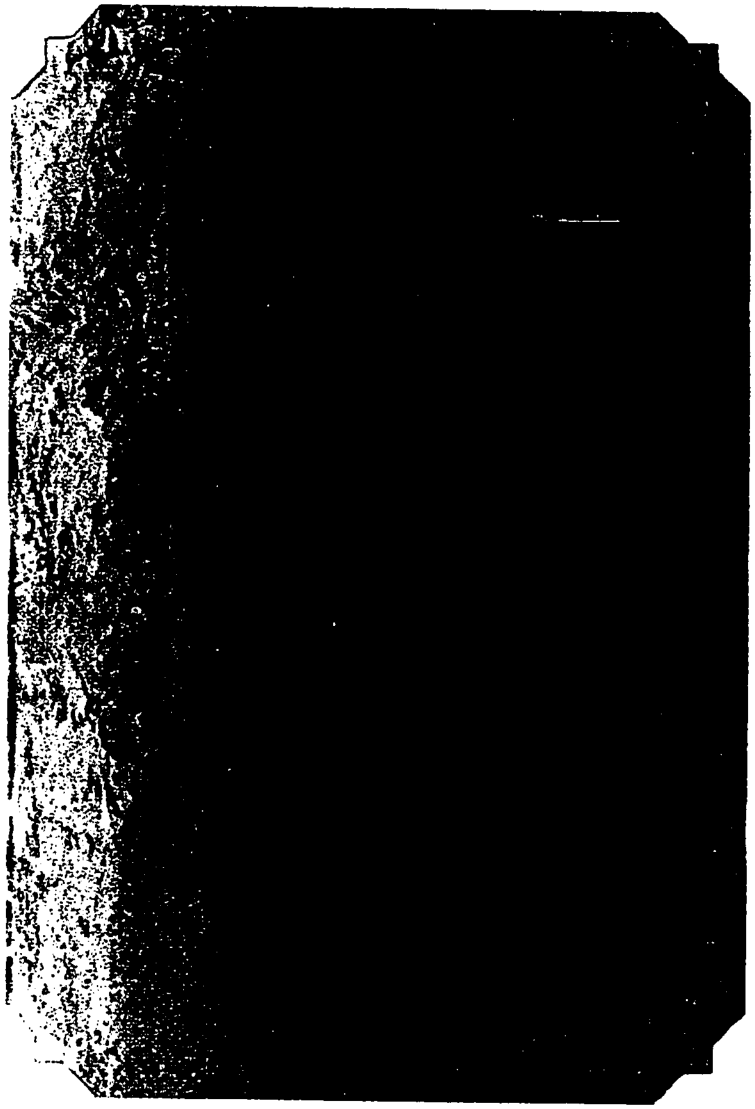


Plate B-16 Column cracks due to transverse loads ignored during design.

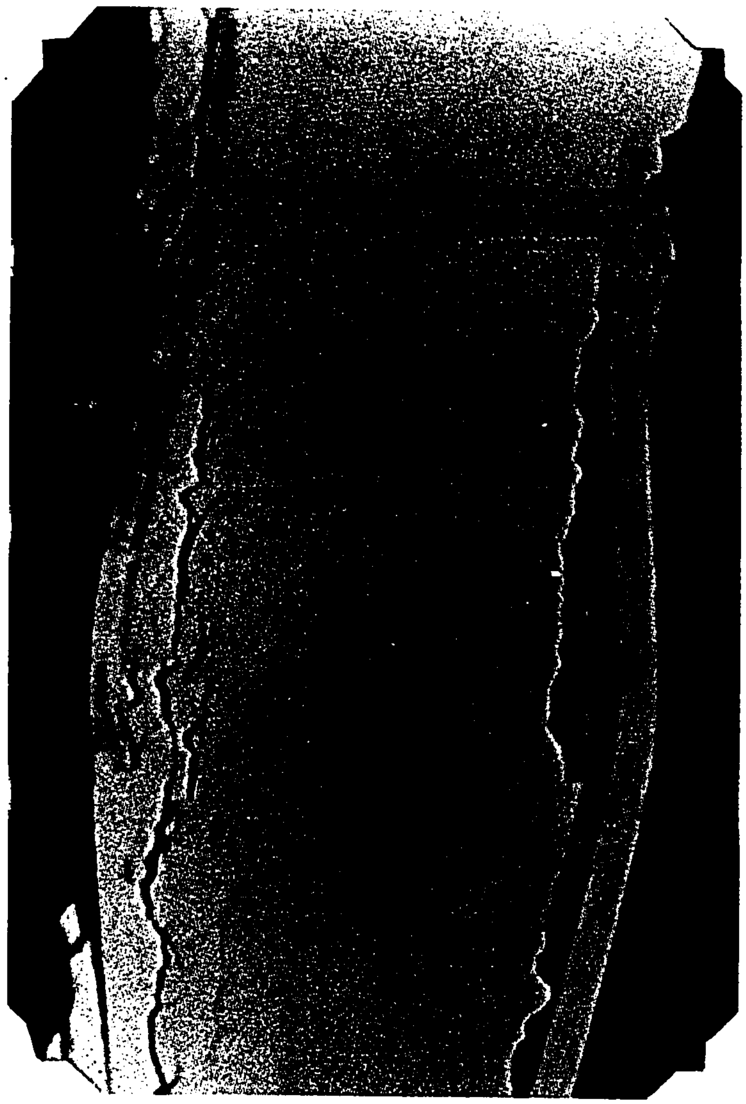


Plate B-17 Column failure and reinforcement bowing.

Appendix - C GURU Design Specifications

Guru Major Design Specifications. *(Guru, 1989)*

Specification Item	**Bounds**
Rule sets	unlimited
Rules per rule set	unlimited
Rule size (characters)	unlimited
Variables per rule set	unlimited
Values per fuzzy variable	255
Built-in certainty factor algebras	16 methods
built-in rule selection strategies	50 methods
Levels of consultation nesting	50
Tables per database	unlimited
Tables open at once	240
Records per table	2,137,483,647
Characters per record	65,535
Fields per record	255
Characters per field	65,534
Numeric floating point representation	IEEE
Command line length (characters)	unlimited
Index keys per table	unlimited
Fields per index key	65,535
Index key length (characters)	65,535
Control break criteria per report	255
Elements per screen or report form	unlimited
Foreground colors per screen form	8
Background colors per screen form	8
Cells per spreadsheet	65,025
Windows per spreadsheet	20
Data observations per graph	unlimited
Graphs per screen	unlimited
Types of graphs	15
Text size (lines)	32,767
Characters per text line	255
Baud rate (bits per second)	38,400
Program length (lines)	unlimited
Working variables	unlimited
Security code combinations	65,535
Command help screens on-line	500+
Menu-guided help pages on-line	400+
Built-in vocabulary words	500+
Words per natural language word list	65,535

Appendix - D Documented defect cases.

CASE S1:
MEMBER : Slab on grade.
PROBLEM : Soil Heaving.

SYMPTOMS :

- Slab is irregular and pumping.
- It often occurs seasonally after a hard rain.
- Active cracks that tend to close and open.
- Slab is not leveled especially at edges.
- Top of column is hugging inwards.

LOCATION : At edge of slab.

CHECKS :

1. Check type of subsoil around the structure.
2. Check slab design.(plans & documents)
3. Check placement of reinforcement (*cover meter)*
4. Check for occurrence of heavy rain, or seasonal variation.

CASE S2 :
MEMBER : Suspended floor slab.
PROBLEM : Differential settlement.

SYMPTOMS :

- Crack running along the wall and restrained corners.
- Top of columns hugging outwards.
- Problem takes a long time to occur.
- Slab edges are not leveled.
- Cracks are deep through the slab.

LOCATION : Around the slab edges.

CHECKS :

1. Check structural design deficiency.
2. Check quality of subsoil. (type, stratum, bearing capacity)
3. Check concrete strength.

CASE S3 :

MEMBER : Concrete slab (elevated or ground slab).

PROBLEM : Sulphate attack.

SYMPTOMS :

- Efflorescence and discoloration of slab.
- Diffused or non pattern cracks radiating from center.
- Slab surface is heaving and plugging.
- Concrete is soft and mushy when damp.

LOCATION : No particular location.

CHECKS :

1. Determine concrete strength.
2. Conduct sulphates content test.
3. Check cement type.
4. Check concrete permeability.
5. Check type aggregates.
6. Check subsoil chemical constituents for possible sulpherous salts.
7. Analyze ground water for possible contamination.

CASE S4 :

MEMBER : Concrete slab (elevated or ground slab).

PROBLEM : Corrosion of reinforcement.

SYMPTOMS :

- Splitting cracks running along reinforcement.
- Spalling of concrete cover.
- Rust stains.

LOCATION : Along the reinforcement.

CHECKS :

1. Perform cover meter test
2. Expose reinforcement.
3. Perform half-cell potential test.

4. Conduct chloride content and depth tests.
5. Conduct carbonates content and depth tests.
6. Check concrete quality.(permeability, used water).
7. Check aggregates quality.
8. Conduct chemical analysis of subsoil.
9. Conduct chemical analysis of ground water.

CASE S5 :
MEMBER : Concrete slabs.
PROBLEM : Drying shrinkage cracking.

SYMPTOMS :

- Irregular or non pattern cracks in all directions with varying lengths.

LOCATION : No particular location.

CHECKS :

1. Check concrete quality. (mixing, finishing, constituents)
2. Check curing practice.
3. Check type of aggregates.
4. Check cement content.
5. Check water content.

CASE B1 :
MEMBER : Concrete Beam.
PROBLEM : Tension or Flexural Cracking.

SYMPTOMS :

- Vertical cracks, wide and varying in length.

LOCATION : At locations of the negative moment.

CHECKS :

1. Check for loading estimation and design.
2. Check concrete strength.
3. Check for amount and location of rebars.
4. Check for possible overloading.
5. Check for presence of restrains.

CASE B2 :
MEMBER : Concrete Beam.
PROBLEM : Shear Cracks.

SYMPTOMS :

- Wide, inclined cracks.

LOCATION : Between support and inflection point. (concentrated shear locations)

CHECKS :

1. Review distribution of shear loads.
2. Check adequacy of stirrups and spacing. (cover meter)
3. Check concrete strength.
4. Investigate for possible settlement.

CASE B3 :
MEMBER : Concrete Beam.
PROBLEM : Temperature or Shrinkage Cracks.

SYMPTOMS :

- Shallow, short cracks running in all directions.

LOCATION : At random, at any location.

CHECKS :

1. Check concrete mix design and quality.

2. Check curing practice.
3. Check temperature records.
4. Check aggregate type and quality.

CASE B4 :

MEMBER :	Concrete Beam.
PROBLEM :	Sulphate Attack.

SYMPTOMS :

- White patches and stains, possible discoloration.
- May be accompanied with surface crazing.

LOCATION : No particular location.

CHECKS :

1. Check concrete strength.
2. Check sulphates content.
3. Check concrete constituents for possible contamination.
4. Check curing water.
5. Check for possible spillage of contaminated water.

CASE B5 :

MEMBER :	Concrete Beam.
PROBLEM :	Corrosion of Reinforcement.

SYMPTOMS :

- Cracks running along rebars, vertical and/or horizontal, continuous or intermitted.
- Surface spalling.
- Rust stains.

LOCATION : Any location along rebars, at beam side or bottom.

CHECKS :

1. Locate reinforcement.
2. Expose reinforcement.
3. Conduct half-cell potential.
4. Conduct depth and content of chlorides test.
5. Conduct depth and content of carbonates test.
6. Check concrete permeability.
7. Check aggregates type.
8. Check mixing and curing water quality.

CASE B6 :

MEMBER : Concrete Beam.

PROBLEM : Bond Failure.

SYMPTOMS :

- Continuous or partial splitting of beam bottom cover.

LOCATION : Along reinforcement, at beam side only near ends.

CHECKS :

1. Check rebar size, and placement.
2. Check concrete strength.
3. Check rebar designed development length.

CASE C1:

MEMBER : Concrete Column.

PROBLEM : Corrosion of Reinforcement.

SYMPTOMS :

- Wide cracks running vertically or horizontally along reinforcement.
- Rust stains.

• Pealing and spalling of bulks of concrete surface.

LOCATION : Any location along reinforcement.

CHECKS :

1. Check cover meter.
2. Expose reinforcement.
3. Conduct half-cell potential.
4. Conduct depth and content of chlorides test.
5. Conduct depth and content of carbonates test.
6. Check concrete permeability.
7. Check aggregates type.
8. Check mixing and curing water quality.

CASE C2 :
MEMBER : Concrete Column.
PROBLEM : Buckling of Column.

SYMPTOMS :

• Spalling of concrete cover.
• Separation of rebars from inner concrete.
• Pealing of concrete cover between stirrups.

LOCATION : At various locations along the column.

CHECKS :

1. Check for reinforcement adequacy.
2. Check strength of concrete.
3. Check load distribution.
4. Check for possible overloading.

Appendix - E Implemented Rules.

```
GOAL:  CAUSE

WINDOW:
        ROW:   20
        COLUMN: 10
        DEPTH: 5
        WIDTH:50
        FORG:  M
        BAGC:  U

INITIAL:
        CLEAR
        LOAD FROM MAIN.ICF; LOAD FROM HEAV.ICF; LOAD FROM HEAVCHEK.ICF
        LOAD FROM GEHAD.ICF; LOAD FROM GEHAD2.ICF; LOAD FROM CORR.ICF
        LOAD FROM CORRCHEK.ICF; LOAD FROM SETLCHEK.IC
        LOAD FROM SETTL.ICF; LOAD FROM RECTCHEK.ICF
        LOAD FROM ALKLIAGG.ICF; LOAD FROM SULFATE.ICF
        LOAD FROM SULFCHEK.ICF; LOAD FROM GEHAD1

        E.BEST = 10
        E.TRYP = "R" ; E.MIX = "N" ; E.SORD = "U"  ; E.LSTR = 150 ; E.RIGR = "A"
        E.OFUZ  = 3

        CAUSE = UNKNOWN;  MEMBER = UNKNOWN;  PROBLEM = UNKNOWN
        CL = UNKNOWN;  CO = UNKNOWN;  POT = UNKNOWN
        COVER = UNKNOWN;  PH = UNKNOWN;  SL = UNKNOWN
        SOIL = UNKNOWN;  QUALITY = UNKNOWN;  CEMENT = UNKNOWN
        GWATER  = UNKNOWN;  MIX  = UNKNOWN;  STRENGTH = UNKNOWN
        SUSPECT = UNKNOWN;  PERM  = UNKNOWN;  AGG = UNKNOWN
        MOMENT = UNKNOWN;  STEEL  = UNKNOWN;  BEARCAP = UNKNOWN
        ENV    = UNKNOWN;     SOILCONT = UNKNOWN;  SCRACK  = UNKNOWN
        SSYM    = UNKNOWN;     STIME = UNKNOWN
        SRELATE = UNKNOWN;     SAPPER  = UNKNOWN;     SCONC = UNKNOWN
        CORROS  = UNKNOWN;     EXTERNAL = UNKNOWN;     INTERNAL = UNKNOWN
        SERVICE = UNKNOWN;     ELEMENT  = UNKNOWN

        BLOC    = UNKNOWN;     SHEAR   = UNKNOWN;   BCRACK  = UNKNOWN
        BSYM   = UNKNOWN;     BRELATE = UNKNOWN;     BCONC   = UNKNOWN;
        CRAKLEN = UNKNOWN;     CRAKWID = UNKNOWN;     CRAKDIR = UNKNOWN

        COL    = UNKNOWN;     CLOC    = UNKNOWN;     CCRACK  = UNKNOWN
        CSYM    = UNKNOWN;     SUSPECT = UNKNOWN;     CRAKBEHV = UNKNOWN
        CCONC   = UNKNOWN


        PUTFORM GEHAD; PUTFORM GEHAD1; WAIT; CLEAR
        PUTFORM GEHAD2; WAIT ; CLEAR
        PUTFORM MAIN; GETFORM MAIN; WAIT; CLEAR

DO:
        CLEAR
        /*PUTFORM END*/
```

```
        PUTFORM GEHAD2
        WAIT
        CLEAR
        I = 1
        WHILE CFN (CAUSE,I) > 0
         AT 10+I,1 OUTPUT  "THE CAUSE OF DETERIORATION IS: ", CAUSE(I),
         AT 15+I,1 OUTPUT "THE MEMBER IS SUSPECTED TO HAVE ", PROBLEM(I),
         AT 18+I,1 OUTPUT CFN (CAUSE,I) USING "DDD",
        I = I + 1
        ENDWHILE

RULE:   S111
        TEST:  P
        IF:     MEMBER = "SLAB ON GRADE"
                AND (SCRACK = "CRACKS TEND TO CLOSE AND OPEN"
                OR (SSYM = "SLAB IS IRREGULAR AND PUMPING"
                OR SSYM = "SLAB EDGES ARE NOT LEVELLED")
                OR STIME = "PROBLEM OFTEN OCCURS SEASONALLY, AFTER A HARD
                        RAIN"
                OR SRELATE = "TOP OF COLUMN IS HUGGING INWARDS")
        THEN:   PROBLEM += {"SLAB HEAVING"}
        NEEDS:  MEMBER, SCRACK, SSYM, STIME, SRELATE
        CHANGES:    PROBLEM

RULE:   S120
        TEST:  S
        IF:     PROBLEM = "SLAB HEAVING"
        THEN:  PUTFORM HEAV
                WAIT
                CLEAR
                PUTFORM HEAVCHEK
                WAIT
                CLEAR
        NEEDS:  PROBLEM
        REASON: SLAB HEAVING OCCURANCE IS ACCOMPANIED WITH ACTIVE    \
                CRACKS WHICH MAY CAUSE THE SLAB TO BE PUPMING, OR EVEN\
                WORSE NOT LEVELLED. ANOTHER SEVERE SYMPTOM IS HUGGING \
                OF COLUMNS INWARDS. THE PROBLEM OFTEN OCCURS SEASONALLY\
                AFTER A HARD RAIN.

RULE:   S131
        TEST:  S
        IF:     PROBLEM = "SLAB HEAVING"
                AND NOT (SOIL = "EXPANSIVE SOIL")
                AND MOMENT = "POOR DISTRIBUTION OF BENDING MOMENT"
        THEN:   CAUSE += {"STRUCTURAL FAILURE OF SLAB DUE TO POOR DESIGN"}
        NEEDS:  PROBLEM, SOIL, MOMENT
        CHANGES:    CAUSE

RULE:   S132
        TEST:  S
        IF:     PROBLEM = "SLAB HEAVING"
                AND SOIL = "EXPANSIVE SOIL"
```

```
            AND MOMENT = "ADEQUATE ESTIMATION OF BENDING MOMENT"
            AND STEEL = "BARS ARE POORLY PLACED"
            AND ENV = "OCCURANCE OF HEAVY RAIN, OR SEASONAL VARIATION"
       THEN:  CAUSE += {"IMPROPER PLACEMENT OR LACK OF REINFORCEMENT
                             DURING CONSTRUCTION"}
       NEEDS: PROBLEM, SOIL, MOMENT, STEEL, ENV
       CHANGES:    CAUSE

RULE:  S133
       TEST:  S
       IF:    PROBLEM = "SLAB HEAVING"
              AND SOIL = "EXPANSIVE SOIL"
              AND MOMENT = "POOR DISTRIBUTION OF BENDING MOMENT"
              AND STEEL = "BARS ARE PLACED AS DESIGNED, BUT NOT ADEQUATE"
              AND ENV = "OCCURANCE OF HEAVY RAIN, OR SEASONAL VARIATION"
       THEN:  CAUSE += {"EXISTANCE OF EXPANSIVE SOIL NOT CONSIDERED IN
                             DESIGN"}
       NEEDS: PROBLEM, SOIL, MOMENT, STEEL, ENV
       CHANGES:    CAUSE

RULE:  S211
       TEST:  P
       IF:   MEMBER = "SLAB"
             AND ( SCONC = "CRACKS ARE DEEP THROUGH THE SLAB"
             OR STIME = "PROBLEM OCCURED OVER A CONSIDERABLE TIME"
             OR SSYM = "SLAB EDGES ARE NOT LEVELLED"
             OR (SRELATE = "TOP OF COLUMN IS HUGGING OUTWARDS"
             OR SRELATE = "CRACKS ARE RUNING ALONG WALL, AND RESTRAINED
                             CORNERS"))
       THEN:  PROBLEM += {"SLAB SETTLEMENT"}
       NEEDS: MEMBER, SCONC, STIME, SSYM, SRELATE
       CHANGES:    PROBLEM
       REASON: SLAB SETTLEMENT IS NOT A SUDDEN PROBLEM WHICH IS \
               ACCOMPANIED WITH SPLITTING CRACKS AND MAY CAUSE THE SLAB \
               TO BE NOT LEVELLED.  ANOTHER SEVERE SYMPTOM IS HUGGING OF \
               COLUMNS OUTWARDS. THE CRACKS MAY BE SPREAD AND RUNNING \
               ALONG WALLS AND OTHER RESTRAINED JOINTS.

RULE:  S220
       TEST:  S
       IF:   PROBLEM = "SLAB SETTLEMENT"
       THEN:  PUTFORM SETTL
              WAIT
              CLEAR
              PUTFORM SETLCHEK
              WAIT
              CLEAR
       NEEDS: PROBLEM

RULE:  S231
       TEST:  S
       IF:    PROBLEM = "SLAB SETTLEMENT"
              AND SOIL = "COLLAPSABLE SOIL"
```

```
            AND BEARCAP = "BEARING CAPACITY ESTIMATION IS INACCURATE"
      THEN:  CAUSE += {"EXISTANCE OF COLLAPSABLE SOIL OR CAVITIES THAT WERE
                          IGNORED DURING DESIGN"}
            AT 10,1 OUTPUT CAUSE
      NEEDS:   PROBLEM, SOIL, BEARCAP
      CHANGES: CAUSE

RULE:  S232
      TEST:  S
      IF:      PROBLEM = "SLAB SETTLEMENT"
               AND NOT (SOIL = "COLLAPSABLE SOIL")
               AND BEARCAP = "BEARING CAPACITY ESTIMATION IS SAFE AND
                                ADEQUATE"
               AND MOMENT = "ADEQUATE ESTIMATION OF BENDING MOMENT"
               AND STEEL = "BARS ARE POORLY PLACED"
      THEN:    CAUSE += {"POOR DETAILING OF BARS RESULTING IN RESTRAINING
                          CORNERS AND IMPOSING JOINTS FUNCTION"}
      NEEDS:  PROBLEM, SOIL, BEARCAP, MOMENT, STEEL
      CHANGES:      CAUSE

RULE:  S233
      TEST:  S
      IF:      PROBLEM = "SLAB SETTLEMENT"
               AND (NOT (SOIL = "COLLAPSABLE SOIL")
               OR SOIL = "WELL CONFINED SOIL")
               AND MOMENT = "POOR DISTRIBUTION OF BENDING MOMENT"
               AND BEARCAP = "BEARING CAPACITY ESTIMATION IS INACCURATE"
               AND STEEL = "BARS ARE PLACED AS DESIGNED, BUT NOT ADEQUATE"
      THEN:    CAUSE += {"MISESTIMATION OF LOAD DURING DESIGN AND/OR UNDER
                          ESTIMATION OF SOIL BEARING CAPACITY"}
      NEEDS:  PROBLEM, SOIL, MOMENT, BEARCAP, STEEL
      CHANGES:      CAUSE

RULE:  S234
      TEST:  S
      IF:      PROBLEM = "SLAB SETTLEMENT"
               AND (NOT (SOIL = "COLLAPSABLE SOIL")
               OR SOIL = "WELL CONFINED SOIL")
               AND MOMENT = "ADEQUATE ESTIMATION OF BENDING MOMENT"
               AND BEARCAP = "BEARING CAPACITY ESTIMATION IS SAFE AND
                                ADEQUATE"
               AND STEEL = "BARS ARE PROPERLY PLACED AND ADEQUATE"
               AND STRENGTH = "CONCRETE STRENGTH < SPECIFIED"
               AND SERVICE = "NO SUSPECTED EVENT"
      THEN:      CAUSE += {"POOR CONCRETE QUALITY RESULTING IN STRUCTURAL
                                INADEQUACY"}
      NEEDS:   PROBLEM, SOIL, MOMENT, BEARCAP, STEEL, STRENGTH, SERVICE
      CHANGES:      CAUSE

RULE:  S311
      TEST:  E
      IF:      (MEMBER = "SLAB"
               OR MEMBER = "SLAB ON GRADE" )
```

```
            AND ( SSYM = "SLAB SURFACE IS HEAVING AND PULGING"
            OR SAPPER = "EFFLORESENCE AND DISCOLORATION OF SLAB"
            OR SAPPER = "SLAB IS WHITENED WHEN DRY"
            OR SCRACK = "DIFFUSED OR NON PATTERN CRACKING DEVIATE
                          RADIALY FROM CENTER"
            OR SCONC = "CONCRETE IS SOFT AND MUSHY WHEN DAMP")
      THEN:   SUSPECT = "SULPHATES"
      NEEDS:  MEMBER, SSYM, SAPPER, SCRACK, SCONC
      CHANGES:    SUSPECT
      REASON: SULPHATE ATTACK IS MANIFESITATED THROUGH EFFLORESENCE \
              AND SLAB WHITING WHEN DRY AND LEAVES THE CONCRETE SOFT \
              AND MUSHY WHEN   DAMP. THE SURFACE MAY EXIHIBIT DIFFUSED \
              OR NON PATTERN CRACKING. THE SLAB MAY ULTIMATELY BE  \
              HEAVING AND PULGING.

RULE: S320
      TEST: R
      IF:     SUSPECT = "SULPHATES"
              AND SL = "SULPHATES CONTENT > ALLOWABLE"
      THEN: PROBLEM += {"SULPHATE ATTACK"}
              PUTFORM SULFATE
              WAIT
              CLEAR
              PUTFORM SULFCHEK
              WAIT
              CLEAR
      NEEDS:  SUSPECT, SL
      CHANGES:    PROBLEM

RULE: S331
      IF:     PROBLEM = "SULPHATE ATTACK"
              AND NOT (CEMENT= "TYPE V CEMENT")
              AND (ENV = "ATMOSPHERE POLLUTED WITH SULFUROUS GAS"
              OR ENV = "MARINE ENVIRONMENT")
      THEN:   CAUSE += {"SULPHATE ATTACK DUE TO USE OF WRONG CEMENT TYPE,
                          WHERE EXPOSURE CONDITIONS TO SULPHATES
                          NECCESSIATE THE USE OF SULPHATES RESISTANT
                          CEMENT"}
      NEEDS:  PROBLEM, CEMENT, ENV
      CHANGES:    CAUSE

RULE: S332
      IF:     PROBLEM = "SULPHATE ATTACK"
              AND CEMENT = "TYPE V CEMENT"
              AND SOILCONT = "SOIL IS CONTAMINATED WITH SULFATES"
              AND (NOT (GWATER = "GROUND WATER IS CONTAMINATED WITH
                                   SULPHATES")
              OR GWATER = "GROUND WATER HAS NO NOTICABLE EFFECT")
              AND (NOT (AGG ="AGGREGATES CONTAMINATED WITH SALTS")
              OR AGG = "GOOD QUALITY AGGREGATES")
      THEN:   CAUSE += {"SULPHATE ATTACK DUE TO SOIL CONTAMINATION NOT
                          ALLOWED FOR DURING DESIGN WITH PROPER PROOFING
                          MEASURES"}
```

```
        NEEDS: PROBLEM, CEMENT, SOILCONT, GWATER, AGG
        CHANGES:    CAUSE

RULE: S333
        IF:     PROBLEM = "SULPHATE ATTACK"
                AND CEMENT = "TYPE V CEMENT"
                AND GWATER = "GROUND WATER IS CONTAMINATED WITH SULPHATES"
                AND SOILCONT = "SOIL IS CLEAN AND FREE OF SALTS"
                AND NOT (AGG="AGGREGATES CONTAMINATED WITH SALTS")
        THEN:   CAUSE += {"RISE OF CONTAMINATED GROUND WATER DEPOSITING
                            SULPHATES UNDER THE SLAB "}
        NEEDS: PROBLEM, CEMENT, GWATER, SOILCONT, AGG
        CHANGES:    CAUSE

RULE: S334
        IF:     PROBLEM = "SULPHATE ATTACK"
                AND CEMENT = "TYPE V CEMENT"
                AND AGG = "AGGREGATES CONTAMINATED WITH SALTS"
                AND SOILCONT = "SOIL IS CLEAN AND FREE OF SALTS"
                AND NOT (GWATER="GROUND WATER IS CONTAMINATED WITH
                                    SULPHATES")
        THEN:   CAUSE += {"USE OF CONTAMINATED AGGREGATES RESULTED IN POOR
                            QUALITY CONCRETE LIABLE FOR SULPHATE ATTACK "}
        NEEDS: PROBLEM, CEMENT, AGG, SOILCONT, GWATER
        CHANGES:    CAUSE

RULE: S335
        IF:     PROBLEM = "SULPHATE ATTACK"
                AND CEMENT = "TYPE V CEMENT"
                AND NOT (GWATER="GROUND WATER IS CONTAMINATED WITH
                                    SULPHATES")
                AND NOT (AGG="AGGREGATES CONTAMINATED WITH SALTS")
                AND SOILCONT = "SOIL IS CLEAN AND FREE OF SALTS"
                AND ( ENV = "MARINE ENVIRONMENT"
                OR ENV = "ATMOSHERE POLLUTED WITH SULFUROUS GAS")
                AND  PERM = "CONCRETE IS HIGHLY POROUS"
        THEN:   CAUSE += {"PRODUCTION OF LOW STRENGTH, POROUS CONCRETE
                            DURING CONSTRUCTION INHIBITED THE ATTACK OF
                            SULPHATE SALTS"}
        NEEDS: PROBLEM, CEMENT, GWATER, AGG, SOILCONT, ENV, PERM
        CHANGES:    CAUSE

RULE: S411
        TEST: P
        IF:     (MEMBER = "SLAB"
                OR MEMBER = "SLAB ON GRADE")
                AND (SCRACK = "SPLITTING CRACKS RUNNING ALONG REINFORCEMENT"
                OR SAPPER = "RUST STAINS"
                OR SCONC = "SPALLING OF CONCRETE COVER")
        THEN:   SUSPECT = "CORROSION"
                PUTFORM CLOR; WAIT; CLEAR
        NEEDS: MEMBER, SCRACK, SCONC, SAPPER
        CHANGES:    SUSPECT
```

```
        REASON: THESE SYMPTOMS HELP TO DEFINE THE TYPE OF DEFECT

RULE:   S420
        TEST:  S
        IF:     SUSPECT = "CORROSION"
                AND POT = "POTENTIAL > ALLOWABLE"
        THEN:   CORROS = "CONFIRMED"
        NEEDS:  SUSPECT, POT
        CHANGES:    CORROS
        REASON: YOU NEED TO INPUT THE RESULT OF THE HALF CELL POTENTIAL \
                    TEST TO JUDGE THE OCCURANCE OF CORROSION

RULE:   S421
        TEST:  S
        IF:     CORROS = "CONFIRMED"
                AND CL = "CHLORIDE CONTENT > ALLOWABLE"
        THEN:     PROBLEM += {"CHLORIDES CORROSION OF REINFORCEMENT"}
                PUTFORM CORR1; WAIT; CLEAR
                PUTFORM CORRCHEK; WAIT; CLEAR
        NEEDS:  CORROS, CL
        CHANGES:    PROBLEM
        REASON: THE LEVEL OF CHLORIDES IN CONCRETE ARE NEEDED TO  \
                    FIND THE CAUSE OF CORROSION

RULE:   S422
        TEST:  S
        IF:     CORROS = "CONFIRMED"
                AND PH = "PH VALUE IS NOT WITHIN ALLOWABLE"
                AND CO = "CARBONATES DEPTH > ALLOWABLE"
        THEN:   PROBLEM += {"CARBONATES CORROSION OF REINFORCEMENT"}
                PUTFORM CORR2; WAIT; CLEAR
                PUTFORM CORRCHEK; WAIT; CLEAR
        NEEDS:  CORROS, CL, PH, CO
        CHANGES:    PROBLEM
        REASON: YOU NEED TO INPUT THE RESULT OF CONCRETE CHEMICAL  \
                    ANALYSIS TO DECIDE IF IT IS DUE TO CHLORIDES OR  \
                    CARBONATES

RULE:   S423
        TEST:  P
        IF:     (NOT (PERM = "CONCRETE IS DENSE AND NON-PERMEABLE")
                OR QUALITY = "CONCRETE IS POORLY COMPACTED"
                OR AGG = "AGGREGATES CONTAMINATED WITH SALTS")
        THEN:   INTERNAL = "TRUE"
        NEEDS:  PERM, QUALITY, AGG
        CHANGES: INTERNAL
        REASON: YOU NEED TO INPUT THE RESULTS OF THE PERFORMED TESTS \
                    TO DIAGNOSE THE SOURCE OF CORROSION. PERMIABILITY, \
                    TYPE OF AGGREGATES, AND CONCRETE QUALITY ARE POSSIBLE\
                    CORROSION INHIBITORS
```

```
RULE: S424
        TEST: R
        IF:     MEMBER = "SLAB ON GRADE"
                AND NOT (GWATER ="GROUND WATER IS CONTAMINATED WITH
                                    CORROSIVE SALTS")
                AND NOT (SOILCONT ="SOIL IS CONTAMINATED WITH CORROSIVE
                                    SALTS")
        THEN:   EXTERNAL = "FALSE"
        NEEDS:  MEMBER, GWATER, SOILCONT
        CHANGES: EXTERNAL
        REASON: THE RESULTS OF SOIL AND GROUND WATER CHEMICAL        \
                INVESTIGATION HELP TO DECIDE IF THE SOURCE OF CORROSION \
                IS FROM THE GROUND, IN WHICH CASE THE STRUCTURE MAY NOT \
                BE WELL INSULATED


RULE: S425
        TEST: E
        IF:     MEMBER = "SLAB ON GRADE"
                AND (SOILCONT = "SOIL IS CONTAMINATED WITH CORROSIVE SALTS"
                OR  GWATER ="GROUND WATER IS CONTAMINATED WITH CORROSIVE
                                SALTS"
        THEN:   EXTERNAL = "TRUE"
        NEEDS:   MEMBER, SOILCONT, GWATER
        CHANGES:     EXTERNAL
        REASON: THE RESULTS OF SOIL AND GROUND WATER CHEMICAL        \
                INVESTIGATION HELP TO DECIDE IF THE SOURCE OF CORROSION \
                IS FROM THE GROUND, IN WHICH CASE THE STRUCTURE MAY NOT \
                BE WELL INSULATED

RULE: S426
        TEST: S
        IF:     QUALITY = "GOOD QUALITY CONCRETE"
                AND PERM = "CONCRETE IS DENSE AND NON-PERMEABLE"
                AND NOT (AGG = "AGGREGATES CONTAMINATED WITH SALTS")
        THEN:     INTERNAL = "FALSE"
        REASON: YOU NEED TO INPUT THE RESULTS OF THE PERFORMED TESTS \
                TO DIAGNOSE THE SOURCE OF CORROSION. PERMIABILITY,  \
                TYPE OF AGGREGATES, AND CONCRETE QUALITY ARE POSSIBLE\
                CORROSION INHIBITORS

RULE: S427
        TEST: P
        IF:   PROBLEM = "CHLORIDES CORROSION OF REINFORCEMENT"
                AND EXTERNAL = "TRUE"
                AND INTERNAL = "FALSE"
        THEN:  CAUSE += {"CORROSION DUE TO SOIL CONTAMINATION OR RISE OF
                            CONTAMINATED GROUND WATER DEPOSITING SALTS
                            UNDER THE SLAB NOT PROTECTED AGAINST WITH
                            COINTER MEASURES"}
        NEEDS:  PROBLEM, EXTERNAL, INTERNAL
        CHANGES:     CAUSE
```

```
RULE:  S428
       TEST:  S
       IF:     PROBLEM = "CHLORIDES CORROSION OF REINFORCEMENT"
               AND EXTERNAL = "FALSE"
               AND INTERNAL = "TRUE"
       THEN:  CAUSE += {"CORROSION DUE TO USE OF POOR QUALITY POROUS
                          CONCRETE LIABLE TO CORROSION."}
       NEEDS:  PROBLEM, EXTERNAL, INTERNAL
       CHANGES: CAUSE

RULE:  S429
       TEST:  S
       IF:    PROBLEM = "CARBONATES CORROSION OF REINFORCEMENT"
               AND INTERNAL = "TRUE"
       THEN:   CAUSE += {"CORROSION DUE TO USE OF POOR QUALITY AGGREGATES
                          THAT INITIATED CONCRETE CORROSION"}
               AT 12,1 OUTPUT CAUSE
       NEEDS:  PROBLEM, INTERNAL
       CHANGES: CAUSE

RULE:  S430
       TEST:  S
       IF:     PROBLEM = "CHLORIDES CORROSION OF REINFORCEMENT"
               AND INTERNAL = "TRUE"
       THEN:  CAUSE += {"CORROSION DUE TO USE OF POOR QUALITY AGGREGATES
                          THAT INITIATED CONCRETE CORROSION"}
       NEEDS:  PROBLEM, INTERNAL
       CHANGES: CAUSE

RULE:  S431
       TEST:  R
       IF:     (PROBLEM = "CARBONATES CORROSION OF REINFORCEMENT"
               OR PROBLEM = "CHLORIDES CORROSION OF REINFORCEMENT")
               AND EXTERNAL = "FALSE"
               AND INTERNAL = "FALSE"
               AND COVER = "CONCRETE COVER IS INADEQUATE"
       THEN:  CAUSE += {"CORROSION DUE TO FAILURE TO PROVIDE SUFFICIENT
                          CONCRETE COVER"}
       NEEDS:  PROBLEM, EXTERNAL, INTERNAL, COVER
       CHANGES:     CAUSE

RULE:  S511
       TEST:  P
       IF:     (MEMBER = "SLAB"
               OR MEMBER = "SLAB ON GRADE")
               AND (SCRACK = "MAP CRACKING, OF IRREGULAR LINKED PATTERN"
               OR SAPPER = "A COLORLESS VISCOUS WHITE GEL THAT SWELLS WATER"
               OR SCONC = "EXPANSION AND CRACKING OF AGGREGATE PARTICLES &
                          CEMENT PASTE")
               AND SSYM = "SLAB SURFACE IS CRACKED AND EXPANDED"
               AND STIME = "PROBLEM OCCURED OVER A CONSIDERABLE TIME"
       THEN:  PROBLEM += {"ALKALI-AGGREGATE REACTION"}
```

```
RULE: S520
      IF:    PROBLEM = "ALKALI-AGGREGATE REACTION"
      THEN:  PUTFORM ALKLIAGG
             WAIT
             CLEAR
             PUTFORM RECTCHEK
             WAIT
             CLEAR

RULE: S531
      IF:    PROBLEM = "ALKALI-AGGREGATE REACTION"
             AND AGG = "AGGREGATES CONTAINING SILCA SALTS"
      THEN:  CAUSE += {"ALKALI-AGGREGATE REACTION DUE TO USE OF
                        CONTAMINATED AGGREGATES"}

RULE: S532
      IF:    PROBLEM = "ALKALI-AGGREGATE REACTION"
             AND NOT (AGG="AGGREGATES CONTAINING SILCA SALTS")
             AND PERM = "CONCRETE IS HIGHLY POROUS"
             AND SOILCONT = "SOIL IS CONTAMINATED WITH SULFATES"
      THEN:  CAUSE += {"ALKALI-AGGREGATE REACTION DUE POOR CONCRETE
                        QUALITY AND CONTAMINATION FROM GROUND SOIL NOT
                        PROTECTED AGAINST"}

RULE: S533
      IF:    PROBLEM = "ALKALI-AGGREGATE REACTION"
             AND NOT (SOILCONT="SOIL IS CONTAMINATED WITH SULFATES")
             AND NOT (AGG ="AGGREGATES CONTAMINATED WITH SILICA SALTS")
             AND PERM = "CONCRETE IS HIGHLY POROUS"
             AND QUALITY = "CONCRETE IS POORLY COMPACTED"
             AND GWATER = "GROUND WATER IS CONTAMINATED WITH CHEMICALS"
      THEN:  CAUSE += {"ALKALI-AGGREGATE REACTION DUE TO USE OF POOR
                        QUALITY CONCRETE LIABLE TO CHEMICAL ATTACK
                        FROM THE GROUND WATER"}

RULE: DUMMY1
      IF:    (MEMBER = "SLAB" OR MEMBER = "SLAB ON GRADE")
             AND SCONC = "NON OF THE ABOVE"
             AND STIME = "NON OF THE ABOVE"
             AND SCRACK = "NON OF THE ABOVE"
             AND SSYM = "NON OF THE ABOVE"
             AND SRELATE = "NON OF THE ABOVE"
             AND SAPPER = "NON OF THE ABOVE"
      THEN:  ELEMENT = "BEAM"
      NEEDS: MEMBER, SRELATE, SCONC, STIME, SSYM, SCRACK, SAPPER
      CHANGES:    ELEMENT

RULE: B111
      TEST:  P
      IF:    MEMBER = "BEAM"
             AND CRAKDIR = "VERTICAL CRACKS"
             AND CRAKWID = "WIDE"
             AND CRAKLEN = "VARYING IN LENGTH"
```

```
        AND BLOC = "AT TOP OF BEAM AT NEGATIVE MOMENT LOCATIONS"
    THEN: PROBLEM = "TENSION OR FLEXURAL CRACKING"
    NEEDS: MEMBER, CRAKDIR, CRAKWID, CRAKLEN
    CHANGES:    PROBLEM

RULE: B120
    TEST: E
    IF:     PROBLEM = "TENSION OR FLEXURAL CRACKING"
    THEN: PUTFORM TENSION
            WAIT
            CLEAR
            PUTFORM TENCHEK
            WAIT
            CLEAR
    NEEDS: PROBLEM

RULE: B131
    IF:     PROBLEM = "TENSION OR FLEXURAL CRACKING"
            AND NOT (SOIL = "EXPANSIVE SOIL" OR SOIL = "COLLAPSABLE SOIL")
            AND BEARCAP = "BEARING CAPACITY ESTIMATION IS SAFE AND
                                    ACCURATE"
            AND MOMENT = "POOR DISTRIBUTION OF BENDING MOMENT"
            AND STEEL = "BARS ARE INADEQUATE"
    THEN: CAUSE = "STRUCTURAL FAILURE OF BEAM DUE TO POOR DESIGN"
    NEEDS: PROBLEM, SOIL, BEARCAP, MOMENT, STEEL
    CHANGES: CAUSE

RULE: B132
    IF:     PROBLEM = "TENSION OR FLEXURAL CRACKING"
            AND (SOIL = "EXPANSIVE SOIL" OR SOIL = "COLLAPSABLE SOIL")
            AND BEARCAP = "BEARING CAPACITY ESTIMATION IS SAFE AND
                                    ACCURATE"
            AND MOMENT = "ADEQUATE ESTIMATION OF BENDING MOMENT"
            AND STEEL = "BARS ARE NOT PLACED AS DESIGNED"
    THEN: CAUSE = "IMPROPER PLACEMENT OR LACK OF REINFORCEMENT DURING
                            CONSTRUCTION"
    NEEDS: PROBLEM, SOIL, BEARCAP, MOMENT, STEEL
    CHANGES: CAUSE

RULE: B133
    IF:     PROBLEM = "TENSION OR FLEXURAL CRACKING"
            AND (SOIL = "EXPANSIVE SOIL" OR SOIL = "COLLAPSABLE SOIL")
            AND MOMENT = "POOR DISTRIBUTION OF BENDING MOMENT"
            AND BEARCAP = "BEARING CAPACITY ESTIMATION IS INACCURATE"
            AND STEEL = "BARS ARE PLACED AS DESIGGNED, BUT NOT ADEQUATE"
    THEN: CAUSE = "EXISTANCE OF POOR SOIL NOT CONSIDERED IN DESIGN"
    NEEDS: PROBLEM, SOIL, MOMENT, BEARCAP, STEEL
    CHANGES:    CAUSE

RULE: B134
    IF:     PROBLEM = "TENSION OR FLEXURAL CRACKING"
            AND NOT (SOIL = "EXPANSIVE SOIL" OR SOIL = "COLLAPSABLE SOIL")
            AND (MOMENT = "ADEQUATE ESTIMATION OF BENDING MOMENT"
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            OR BEARCAP = "BEARING CAPACITY ESTIMATION IS SAFE AND
                          ACCURATE"
            OR STEEL = "BARS ARE PROPERLY PLACED AND ADEQUATE")
            AND SERVICE = "STRUCTURE IS PRACTICING HIGHER LOADS THAN
                          DESIGNED"
  THEN:   CAUSE = "OVERLOADING OF THE STRUCTURE NOT CONSIDERED IN DESIGN"
  NEEDS:  PROBLEM, SOIL, MOMENT, BEARCAP, STEEL, SERVICE
  CHANGES:    CAUSE

RULE: B211
      IF:     MEMBER = "BEAM"
              AND CRAKDIR = "INCLINED CRACKS"
              AND BLOC = "BETWEEN SUPPORT AND MOMENT INFLECTION
                        (CONCENTRATED SHEAR)"
      THEN:   PROBLEM = "SHEAR CRACKS"
      NEEDS:  MEMBER, CRAKDIR, BLOC
      CHANGES: PROBLEM

RULE: B220
      IF:     PROBLEM = "SHEAR CRACKS"
      THEN:  PUTFORM SHEAR
              WAIT
              CLEAR
              PUTFORM SHERCHEK
              WAIT
              CLEAR
      NEEDS:  PROBLEM

RULE: B231
      IF:     PROBLEM = "SHEAR CRACKS"
              AND SHEAR = "POOR DISTRIBUTION OF SHEAR LOAD"
              AND STEEL = "STIRRUPS ARE INADEQUATE OR POORLY PLACED"
      THEN:  CAUSE = "SHEAR FAILURE OF BEAM DUE TO POOR DESIGN"
      NEEDS:  PROBLEM, SHEAR, STEEL
      CHANGES: CAUSE

RULE: B232
      IF:     PROBLEM = "SHEAR CRACKS"
              AND (SHEAR = "ADEQUATE ESTIMATION OF SHEAR LOAD"
              OR STEEL = "STIRRUPS ARE ADEQUATE AND PROPERLY PLACED")
              AND STRENGTH = "CONCRETE STRENGTH < SPECIFIED"
              AND (QUALITY = "CONCRETE IS POORLY COMPACTED"
              OR MIX = "LOW CEMENT CONTENT")
      THEN:   CAUSE = "SHEAR FAILURE OF BEAM DUE TO USE OF POOR QUALITY
                        CONCRETE"
      NEEDS:  PROBLEM, SHEAR, STEEL, STRENGTH, QUALITY, MIX
      CHANGES: CAUSE

RULE: B233
      IF:     PROBLEM = "SHEAR CRACKS"
              AND (SHEAR = "ADEQUATE ESTIMATION OF SHEAR LOAD"
              OR STEEL = "STIRRUPS ARE ADEQUATE AND PROPERLY PLACED")
              AND STRENGTH = "CONCRETE STRENGTH IS AS SPECIFIED"
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          AND (NOT (QUALITY = "CONCRETE IS POORLY COMPACTED")
          OR MIX = "MIX DESIGN IS ADEQUATE AND SAFE")
     THEN:  CONSULT DIRECT SLAB3 TO EXECUTE S231,S232,S233,S234
     NEEDS:  PROBLEM, SHEAR, STEEL, STRENGTH, QUALITY, MIX
     CHANGES: CAUSE

RULE:  B311
     IF:      MEMBER = "BEAM"
          AND ((BSYM = "EFFLORESENCE AND DISCOLORATION OF BEAM"
          OR BSYM = "WHITE PATCHES AND STAINS WHEN DRY")
          OR CRAKDIR = "SURFACE CRAZING"
          OR BCONC = "CONCRETE IS SOFT AND MUSHY WHEN DAMP")
          AND BLOC = "AT RANDOM AT ANY LOCATION"
     THEN:  SUSPECT  = "SULPHATES"
     NEEDS:  MEMBER, CRAKDIR, BCONC, BSYM, BLOC
     CHANGES: SUSPECT

RULE:  B320
     IF:      SUSPECT = "SULPHATE ATTACK"
          AND SO = "SULFATES CONTENT > ALLOWABLE"
     THEN:  PROBLEM = "SULPHATE ATTACK"
          PUTFORM SULFATE
          WAIT
          CLEAR
          PUTFORM SULFCHEK
          WAIT
          CLEAR
     NEEDS:  SUSPECT, SO
     CHANGES:      PROBLEM

RULE:  B331
     IF:      PROBLEM = "SULPHATE ATTACK"
          AND NOT (CEMENT= "TYPE V CEMENT")
          AND (ENV = "ATMOSPHERE POLLUTED WITH SULFUROUS GAS"
          OR ENV = "MARINE ENVIRONMENT")
     THEN:  CAUSE = "SULPHATE ATTACK DUE TO USE OF WRONG CEMENT TYPE IN A
                         HARSH ENVIRONMENT LIABLE FOR DETERIORATION"
     NEEDS:  PROBLEM, CEMENT, ENV
     CHANGES:      CAUSE

RULE:  B332
     IF:      PROBLEM = "SULPHATE ATTACK"
          AND CEMENT = "TYPE V CEMENT"
          AND (ENV = "ATMOSPHERE POLLUTED WITH SULFUROUS GAS"
          OR ENV = "MARINE ENVIRONMENT")
          AND AGG="AGGREGATES CONTAMINATED WITH SALTS"
     THEN:  CAUSE = "USE OF CONTAMINATED AGGREGATES RESULTED IN POOR
                         QUALITY CONCRETE LIABLE FOR SULPHATE ATTACK "
     NEEDS:  PROBLEM, CEMENT, ENV, AGG
     CHANGES:      CAUSE
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RULE: B333
    IF:     PROBLEM = "SULPHATE ATTACK"
            AND CEMENT = "TYPE V CEMENT"
            AND (ENV = "ATMOSPHERE POLLUTED WITH SULFUROUS GAS"
            OR ENV = "MARINE ENVIRONMENT")
            AND NOT (AGG = "AGGREGATES CONTAMINATED WITH SALTS")
            AND QUALITY = "CONCRETE IS POORLY COMPACTED"
            AND PERM = "CONCRETE IS HIGHLY POROUS"
    THEN:   CAUSE = "PRODUCTION OF POOR QUALITY POROUS CONCRETE LIABLE
                         FOR SULPHATE ATTACK"
    NEEDS: PROBLEM, CEMENT, ENV, AGG, QUALITY, PERM
    CHANGES:     CAUSE

RULE: B411
    IF:     MEMBER = "BEAM"
            AND ((CRAKWID = "SPLITTING"
            AND CRAKLEN = "RUNNING ALONG REINFORCEMENT")
            OR BSYM = "RUST STAINS"
            OR BCONC = "SPALLING OF CONCRETE COVER")
            AND BLOC = "ALONG REINFORCEMENT, AT BEAM SIDE OR BOTTOM"
    THEN:   SUSPECT = "CORROSION"
    NEEDS:  MEMBER, CRAKWID, CRAKLEN, BSYM, BCONC, BLOC
    CHANGES: SUSPECT

RULE: B420
    IF:     SUSPECT = "CORROSION OF REINFORCEMENT"
            AND (CL = "CHLORIDE CONTENT > ALLOWABLE"
            OR CO = "CARBONATES CONTENT  > ALLOWABLE"
            OR PH = "PH VALUE IS NOT WITHIN ALLOWABLE"
            OR POT = "POTENTIAL IS > ALLOWABLE")
    THEN:   PROBLEM = "CORROSION OF REINFORCEMENT"
            PUTFORM CORR
            WAIT
            CLEAR
            PUTFORM CORRCHEK
            WAIT
            CLEAR
    NEEDS: SUSPECT, CL, CO, PH, POT
    CHANGES:     PROBLEM

RULE: B431
    IF:     PROBLEM = "CORROSION OF REINFORCEMENT"
            AND COVER = "CONCRETE COVER IS ADEQUATE"
            AND PERM = "CONCRETE IS HIGHLY POROUS"
            AND NOT (AGG="AGGREGATES CONTAMINATED WITH SALTS")
            QUALITY = "CONCRETE IS POORLY COMPACTED"
    THEN:   CAUSE = "CORROSION DUE TO USE OF POOR QUALITY CONCRETE LIABLE
                         TO CORROSION"
    NEEDS: PROBLEM, AGG, COVER, PERM, QUALITY
    CHANGES: CAUSE
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RULE: B432
      IF:     PROBLEM = "CORROSION OF REINFORCEMENT"
              AND NOT (AGG="AGGREGATES CONTAMINATED WITH SALTS")
              AND PERM = "CONCRETE IS DENSE AND NON-PERMEABLE"
              AND COVER = "CONCRETE COVER IS INADEQUATE"
      THEN:   CAUSE = "CORROSION DUE TO FAILURE TO PROVIDE SUFFICIENT
                          CONCRETE COVER"
      NEEDS:  PROBLEM, AGG, PERM, COVER
      CHANGES: CAUSE

RULE: B433
      IF:     PROBLEM = "CORROSION OF REINFORCEMENT"
              AND PERM = "CONCRETE IS DENSE AND NON-PERMEABLE"
              AND COVER = "CONCRETE COVER IS ADEQUATE"
              AND NOT (QUALITY="CONCRETE IS POORLY COMPACTED")
              AND AGG = "AGGREGATES CONTAMINATED WITH SALTS"
      THEN:   CAUSE = "CORROSION DUE TO USE OF POOR QUALITY AGGREGATES
                          THAT INITIATED CONCRETE CORROSION"
      NEEDS:  PROBLEM, PERM, COVER, QUALITY, AGG
      CHANGES: CAUSE

RULE: B511
      IF:     MEMBER = "BEAM"
              AND CRAKLEN = "SHORT CRAKS"
              AND CRAKDIR = "RUNNING IN ALL DIRECTIONS"
              AND CRAKWID = "SHALLOW"
              AND BLOC = "AT RANDOM AT ANY LOCATION"
      THEN:   PROBLEM = "TEMPRATURE OR SHRINKAGE CRACKS"
      NEEDS:  MEMBER, CRAKDIR, CRAKLEN, CRAKWID, BLOC
      CHANGES: PROBLEM

RULE: B520
      IF:     PROBLEM = "TEMPRATURE OR SHRINKAGE CRACKS"
      THEN:   PUTFORM TEMP
              WAIT
              CLEAR
              PUTFORM TEMPCHEK
              WAIT
              CLEAR

RULE: B531
      IF:     PROBLEM = "TEMPRATURE OR SHRINKAGE CRACKS"
              AND QUALITY = "CURING PRACTICE IS POOR AND IRREGULAR"
              AND NOT (AGG = "HIGHLY POROUS AGGREGATES")
              AND WC = "W/C CONTENT IS ADEQUATE"
      THEN:   CAUSE = "SHRINKAGE CRACKING DUE TO INSUFFICIENT CURING WHILE
                          CONSTRUCTION"
      NEEDS:  PROBLEM, QUALITY, AGG, WC
      CHANGES:      CAUSE
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RULE: B532

IF: PROBLEM = "TEMPRATURE OR SHRINKAGE CRACKS"
AND QUALITY = "CURING PRACTICE IS PROPER AND THOROUGH"
AND AGG = "HIGHLY POROUS AGGREGATES"
AND WC = "W/C CONTENT IS ADEQUATE"
AND MIX = "MIX DESIGN IS ADEQUATE AND SAFE"
THEN: CAUSE = "SHRINKAGE CRACKING DUE TO USE OF POOR QUALITY AGGREGATES DURING CONSTRUCTION"
NEEDS: PROBLEM, QUALITY, AGG, WC, MIX
CHANGES: CAUSE

RULE: B533

IF: PROBLEM = "TEMPRATURE OR SHRINKAGE CRACKS"
AND QUALITY = "CURING PRACTICE IS PROPER AND THOROUGH"
AND (NOT (AGG = "HIGHLY POROUS AGGREGATES")
OR AGG = "GOOD QUALITY AGGREGATES")
AND (WC = "W/C CONTENT IS HIGH"
OR WC = "ADDITIONAL WATER WAS ADDED DURING CONCRETING")
AND MIX = "MIX DESIGN IS ADEQUATE AND SAFE"
THEN: CAUSE = "SHRINKAGE CRACKING DUE TO ADDING HIGH WATER CONTENT DURING CONSTRUCTION"
NEEDS: PROBLEM, QUALITY, AGG, WC, MIX
CHANGES: CAUSE

RULE: B611

IF: MEMBER = "BEAM"
AND CRAKWID = "SPLITTING"
AND NOT (BSYM = "RUST STAINS")
AND BCONC = "CONTINUOUS OR PARTIAL SPLITTING OF BEAM BOTTOM COVER"
AND BLOC = "ALONG BOTTOM REINFORCEMENT AT BEAM SIDE ONLY"
THEN: PROBLEM = "BOND FAILURE"
NEEDS: MEMBER, CRAKWID, BSYM, BCONC, BLOC
CHANGES: PROBLEM

RULE: DUMMY

IF: MEMBER = "BEAM"
AND BCONC = "NON OF THE ABOVE"
AND CRAKLEN = "NON OF THE ABOVE"
AND CRAKWID = "NON OF THE ABOVE"
AND BSYM = "NON OF THE ABOVE"
AND CRAKDIR = "NON OF THE ABOVE"
THEN: ELEMENT = "COLUMN"
NEEDS: MEMBER, BCONC, CRAKLEN, BSYM, CRAKWID, CRAKDIR
CHANGES: ELEMENT

RULE: C111

IF: MEMBER = "COLMUN"
AND (CCRACK = "ONLY VERTICAL CRACKS"
AND CRAKBEHV = "LOCALLY CONCENTRATED CRACKS"
OR CCONC = "PEALING OF CONCRETE COVER AT INTERVALS")
AND CLOC = "AT VARIOUS LOCATIONS ALONG THE COLUMN"
THEN: PROBLEM = "COLUMN BUCKLING"

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        NEEDS:  MEMBER, CCRACK, CRAKBEHV, CCONC, CLOC
        CHANGES:     PROBLEM

RULE:  C120
        TEST:  E
        IF:       PROBLEM = "COLUMN BUCKLING"
        THEN:   PUTFORM BUCKL
                  WAIT;  CLEAR
                  PUTFORM BUKLCHEK
                  WAIT;  CLEAR
        NEEDS:  PROBLEM

RULE:  C131
        IF:       PROBLEM = "COLUMN BUCKLING"
                  AND (MOMENT = "POOR DISTRIBUTION OF BENDING MOMENT"
                  AND STEEL = "BARS ARE INADEQUATE"
                  AND STRENGTH = "CONCRETE STRENGTH IS AS SPECIFIED"
                  OR COL = "COLUMN SLENDERNESS RATIO IS < ALLOWABLE")
        THEN:   CAUSE = "STRUCTURAL FAILURE OF COLUMN DUE TO POOR DESIGN"
        NEEDS:  PROBLEM, MOMENT, STEEL, STRENGTH
        CHANGES:     CAUSE

RULE:  C132
        IF:       PROBLEM = "COLUMN BUCKLING"
                  AND MOMENT = "ADEQUATE ESTIMATION OF BENDING MOMENT"
                  AND (STEEL = "BARS ARE NOT PLACED AS DESIGNED"
                  OR STEEL = "STIRRUPS ARE INADEQUATE OR POORLY PLACED")
                  AND STRENGTH = "CONCRETE STRENGTH IS AS SPECIFIED"
        THEN:   CAUSE = "COLUMN BUCKLING DUE TO IMPROPER PLACEMENT OR LACK
                              OF REINFORCEMENT DURING CONSTRUCTION"
        NEEDS:  PROBLEM, MOMENT, STEEL, STRENGTH
        CHANGES:     CAUSE

RULE:  C133
        IF:       PROBLEM = "COLUMN BUCKLING"
                  AND MOMENT = "ADEQUATE ESTIMATION OF BENDING MOMENT"
                  AND STEEL = "BARS ARE PROPERLY PLACED AND ADEQUATE"
                  AND STRENGTH = "CONCRETE STRENGTH IS AS SPECIFIED"
                  AND COL = "COLUMN SLENDERNESS RATIO IS SAFE"
                  AND SERVICE = "STRUCTURE IS PRACTICING HIGHER LOADS THAN
                                    DESIGNED"
        THEN:   CAUSE = "COLUMN BUCKLING DUE TO OVERLOADING OF THE
                              STRUCTURE NOT CONSIDERED IN DESIGN"
        NEEDS:  PROBLEM, MOMENT, STEEL, STRENGTH, SERVICE
        CHANGES:     CAUSE

RULE:  C211
        IF:       MEMBER = "COLUMN"
                  AND ((CRAKBEHV = "SPLITTING CRACKS"
                  AND CCRACK = "VERTICAL AND/OR HORIZONTAL.CRACKS")
                  OR CSYM = "RUST STAINS"
                  OR CCONC = "SPALLING OF CONCRETE COVER")
                  AND CLOC = "ANY LOCATION ALONG REINFORCEMENT"
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        THEN:  SUSPECT = "CORROSION OF REINFORCEMENT"
        NEEDS:  MEMBER, CRAKBEHV, CCRACK, CSYM, CCONC, CLOC
        CHANGES: SUSPECT

RULE:  C220
        IF:      SUSPECT = "CORROSION OF REINFORCEMENT"
                 AND (CL = "CHLORIDE CONTENT > ALLOWABLE"
                 OR CO = "CARBONATES CONTENT  > ALLOWABLE"
                 OR PH = "PH VALUE IS NOT WITHIN ALLOWABLE"
                 OR POT = "POTENTIAL IS > ALLOWABLE")
        THEN:  PROBLEM = "CORROSION OF REINFORCEMENT"
                 PUTFORM CORR
                 WAIT
                 CLEAR
                 PUTFORM CORRCHEK
                 WAIT
                 CLEAR
        NEEDS:  SUSPECT, CL, CO, PH, POT
        CHANGES:     PROBLEM

RULE:  C231
        IF:      PROBLEM = "CORROSION OF REINFORCEMENT"
                 AND COVER = "CONCRETE COVER IS ADEQUATE"
                 AND PERM = "CONCRETE IS HIGHLY POROUS"
                 AND NOT (AGG = "AGGREGATES CONTAMINATED WITH SALTS")
                 QUALITY = "CONCRETE IS POORLY COMPACTED"
        THEN:  CAUSE = "CORROSION DUE TO USE OF POOR QUALITY CONCRETE LIABLE
                              TO CORROSION"
        NEEDS:  PROBLEM, AGG, COVER, PERM, QUALITY
        CHANGES: CAUSE

RULE:  C232
        IF:      PROBLEM = "CORROSION OF REINFORCEMENT"
                 AND NOT (AGG = "AGGREGATES CONTAMINATED WITH SALTS")
                 AND PERM = "CONCRETE IS DENSE AND NON-PERMEABLE"
                 AND COVER = "CONCRETE COVER IS INADEQUATE"
        THEN:  CAUSE = "CORROSION DUE TO FAILURE TO PROVIDE SUFFICIENT
                              CONCRETE COVER"
        NEEDS:  PROBLEM, AGG, PERM, COVER
        CHANGES: CAUSE

RULE:  C233
        IF:      PROBLEM = "CORROSION OF REINFORCEMENT"
                 AND PERM = "CONCRETE IS DENSE AND NON-PERMEABLE"
                 AND COVER = "CONCRETE COVER IS ADEQUATE"
                 AND NOT (QUALITY = "CONCRETE IS POORLY COMPACTED")
                 AND AGG = "AGGREGATES CONTAMINATED WITH SALTS"
        THEN:  CAUSE = "CORROSION DUE TO USE OF POOR QUALITY AGGREGATES
                              THAT INITIATED CONCRETE CORROSION"
        NEEDS:  PROBLEM, PERM, COVER, QUALITY, AGG
        CHANGES: CAUSE

END:
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